THERMAL MANIKIN EVALUATION OF MATERIAL COMPONENT AND DESIGN FEATURES ON HEAT AND MOISTURE TRANSFER OF QUADGARD™

By

CATHY L. STARR

Bachelor of Science in Design, Housing &
Merchandising
Oklahoma State University
Stillwater, OK
1998

Master of Science in Design, Housing & Merchandising
Oklahoma State University
Stillwater, OK
2002

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
July, 2010

THERMAL MANIKIN EVALUATION OF MATERIAL

COMPONENT AND DESIGN FEATURES ON HEAT

AND MOISTURE TRANSFER OF QUADGARD™

Dissertation Approved:

Dr. Donna H. Branson

Dissertation Adviser

Dr. Huantian Cao

Dr. Semra Peksoz

Dr. Bill Warde

Dr. A. Gordon Emslie

Dean of the Graduate College

ACKNOWLEDGMENTS

I would like to gratefully and sincerely thank Dr. Donna H. Branson for her guidance, understanding, patience, and most importantly, her friendship during my graduate studies at Oklahoma State University. Her mentorship was paramount in providing a well-rounded experience consistent with my long-term career goals. She encouraged me to not only grow as a researcher but also as an instructor and an independent thinker. For all you have done for me, Dr. Branson, I thank you. I would also like to thank my doctoral committee members, Dr. Huantian Cao, Dr. Semra Peksoz, and Dr. Bill Warde for their support and beneficial contribution, valuable discussions and accessibility. I would also like to thank the entire IPART research group for their support and assistance, especially Panagiotis Kamenidis. Panos kept Walter functioning and without him, I would not have been able to complete this study.

Finally, and most importantly, I would like to thank my family for their unconditional love and support all of these years. My husband, Bill, for all his support, encouragement, and unwavering faith in me were undeniably the foundation upon which I leaned. My father, Charles Paul Brecheisen and my children: Christina, Candace, Breck, and Josh, for being my cheerleaders; they believed in me when I did not. I could never have completed this project without all of you believing in me and supporting my dream. Finally, a special thank to all my professors, family, and friends for their encouragement, support, and prayers.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Today, as in earlier wars, soldiers must wear heavy protective clothing systems, often referred to as body armor, to protect them in battle. Protection has evolved from rigid metal body armor to more ergonomically functional layers of fabrications and rigid plates. As technology advances, new textiles and garment design features are combined to provide higher levels of protection plus improved mobility. Each new generation of body armor is designed to offer increased protection and safety to the soldier by slowing or dispersing the energy from the ballistic projectile; thereby, reducing the number and severity of wounds (Smith, 2006).

Since the introduction of Kevlar® (a trade name for a tougher-than-steel aramid fiber) in 1975, the mortality for U.S. troops from battle injuries has fallen from 30% in WWII, to 24% in Vietnam, to 10% in Iraq (Rosenfeld & Lennarson, 2005; Selle, 2004). Multiple sources credit the advances in body armor and battlefield first aid with increased survival statistics of wounds that would have been fatal in the past (Aisen, 2004; Connolly, 2004). Body armor, however, has significant drawbacks. The soldier is still faced with the dilemma of additional weight, motion restriction, and impediment of heat exchange with the environment from body armor. Military helmets and ballistic protective vests are central to protecting a soldier from small firearms and flying shrapnel. Because of the use of this body armor, soldiers with upper-body wounds have survived, although the usage of improvised explosive devices (IEDs) and "vehicular-borne improvised explosive devices" leave the neck, face, skull base, pelvis, lower abdomen, and extremities vulnerable and are the most common source of severe penetrating and blast trauma in Iraq (Peake, 2005; Rosenfeld, 2005). In response to the enhancement of vehicles' armor, the insurgents have elevated their explosive devices off the ground and placed them strategically to cause more devastating effects in terms of fragment wounds and to increase the number of injured personnel (Peake, 2005). Devastating limb injuries, 6% resulting in amputation, led to concern for providing fragmentation protection from IEDs for the arms and legs. This, in turn, led to the collaborative development of QuadGard™, an arm and leg protection system, at Oklahoma State University. Partners in QuadGard™ development included: FSTechnology LLC, the Naval Research Laboratory, and the Army Research Laboratory.

The design of ballistic and blast protective gear has conflicting requirements; the need to protect the body from flying shrapnel and small fire arms with layers of fabrics which may confound the body's ability to maintain thermal regulation. The extent to which protective clothing affects the heat exchange between the person and the environment is a crucial factor that should be considered when evaluating the design and effectiveness of protective clothing systems worn by the military. QuadGard™ provides the soldier with lightweight and flexible limb body armor. Although the primary function of QuadGard™ is to protect soldiers against the loss of limbs from roadside explosives and small arms, the thermal properties of QuadGard™ are important issues that should be addressed. When the extremities are fitted with thermal retentive ballistic materials, body heat loss is reduced which may lead to heat stress resulting in heat exhaustion or heat stroke. Fanger demonstrated, in his seminal book, *Thermal Comfort*, that human thermal environments are defined by the interaction of the following six factors: air temperature, radiant temperature, humidity, air movement, metabolic heat generated by human activity and clothing worn by a person (1970). Researchers agree that a major factor contributing to comfort is the movement of heat and moisture through a garment system (Das, Das, Kothari, Fanguiero, & de Araujo, 2007; Anderson, 1999; Gibson, 1993; Hatch, Woo, Barker, Radhakrishnaiah, Markee, & Maibach, 1990; Fourt & Hollies, 1970). Research shows that properties of clothing materials critically influence the comfort and performance of the wearer (Zhang, Gong, Yanai, & Tokura, 2002). A fundamental concept identified by Fourt & Hollies is that clothing serves as more than just a cover, it interacts with and modifies the heat regulating function of the skin and has effects that are modified by body movement (1970). Ideally, clothing should protect against environmental changes, and transfer heat and moisture away from the body (Anderson, 1999). The design of protective clothing should be such that heat balance can be maintained.

Exertional Heat Illness (EHI) has received widespread attention due to global warming and recent military deployments to extremely hot environments (Carter, Cheuvront, Williams, Kolka, Stephenson, Sawka, & Amoroso, 2005; O'Brien, McPherson, Alsip, & Sawka, 2003). The human body is susceptible to heat illness from physical exertion when it must perform strenuous physical activity for an extended amount of time (Carter, et al., 2005). "Brigadier General Michael B. Cates, commander of the U.S. Army Center for Health Promotion and Preventive Medicine, reported more than 1,700 heat-related incidences in 2005" (Coleman, 2006, p. 5). Of those incidences, 258 people suffered from heat stroke and 1,467 suffered from heat exhaustion (Coleman, 2006). Heat stress can impair individuals' abilities to perform complex tasks (Havenith, 1999). Dr. John Campbell, U. S. Army Combat Readiness Center Command Surgeon, states heat injuries can be prevented by staying hydrated and watching each other for the following early warning signs of heat stress: that is, dizziness, headache, nausea, unsteady walk, weakness or fatigue, and muscle cramps (Coleman, 2006). These statistics suggest a need for military clothing ensembles that do not negatively inhibit the process of body thermoregulation.

It is well known that extreme environments can reduce the human body's ability to perform or react effectively (Parsons, 2003; Havenith, 1999). Furthermore, when human thermal environments (air temperature, radiant temperature, humidity, air velocity, clothing, and/or physical activity) provide a predisposition for heat storage, the body's thermoregulation system attempts to increase heat loss. "The human body's response can be powerful and effective but it can also incur a strain on the body (and sufficient heat may not be removed), which can become intolerable and eventually lead to heat illness and death (Parsons, 2003, p. 258)." Therefore, there are situations, such as, when soldiers are wearing highly insulative ballistic protection that limit thermal transmittance, and are engaging in rigorous physical activity in hot and humid environmental conditions, where the body's physiological response alone is often an insufficient means of thermoregulation. If ballistic protection does not allow for sufficient heat transfer, soldiers' lives are placed in jeopardy, as the body's basic physiological mechanisms associated with thermoregulation are impaired. Thus, design of ballistic and blast protective clothing requires a delicate balance between meeting protection and thermal criteria.

Purpose

The purpose of this study was to assess and compare the effects of fabrication and design features on heat and moisture transfer performance of three different QuadGard™ systems: QuadGard™ II, QuadGard™ IV, and QuadGard™ V. The QuadGard™ systems researched in this study will also be referred to as: QG II, QG IV Not ventilated, QG IV Ventilated, QG V, QG V Arms, QG V Legs, QG V Upper arms, and QG V Upper legs.

Objectives

The basic focus of this research was to carry out a systematic study to compare three versions of the QuadGard™ system in terms of their thermal and evaporative resistance, micro-climate temperature, and moisture retention. Dry thermal resistance as measured by a sweating thermal manikin is the total thermal resistance of the clothing ensemble and surface air layer; whereas, intrinsic clothing insulation was calculated by subtracting the effect of the surface air layer from the dry thermal resistance. Evaporative resistance as measured by a sweating thermal manikin is the total evaporative resistance of the clothing ensemble and surface air layer; whereas, intrinsic evaporative resistance of the clothing ensemble was calculated by subtracting the effect of the surface air layer from the evaporative resistance. QuadGard™ II and IV were designed to feature sewn-in ballistic panels, while QuadGard™ V was designed to feature insertable packets of ballistic material covered in Rip-stop® (a durable plain weave, nylon fabric), therefore, this study was conducted in two phases. Phase 1 focused on comparing

QuadGard™ II with QuadGard™ IV Ventilated, and QuadGard™ IV Not Ventilated. Phase 2 focused on comparing five configurations of QuadGard™ V.

Hypotheses

Phase 1

H1-1$_0$: There is no significant difference in intrinsic clothing insulation, intrinsic evaporative resistance of the clothing ensemble, micro-climate temperature, and moisture retention among QuadGard™ armor systems II, IV *Ventilated*, and IV *Not Ventilated*.

H1-2$_0$: There is no significant difference in intrinsic clothing insulation, intrinsic evaporative resistance of the clothing ensemble among ballistic materials, Kevlar® and Dyneema®.

Phase 2

H2-1$_0$: There is no significant difference in intrinsic clothing insulation, intrinsic evaporative resistance of the clothing ensemble among QuadGard™ armor systems V, V *Arms*, V *Legs*, V *Upper Arms*, and V *Upper Legs*.

H2-2$_0$: There is no significant difference in intrinsic clothing insulation, intrinsic evaporative resistance of the clothing ensemble among ballistic materials, Kevlar® and Dyneema®.

Limitations

1. This study was limited to comparing and evaluating the effects of only two ballistic fabrications on heat and moisture transfer performance of three different QuadGard™ systems: QuadGard™ II, QuadGard™ IV, and QuadGard™ V.
2. This study was limited to tests performed using a sweating, thermal manikin designed to simulate human thermal interaction with the environment. So the conclusions cannot be generalized to humans.
3. This study was limited to one set of environmental temperature and RH conditions, minimal air movement, and no movement of the manikin.

Definitions

Absorption – a condition in which liquid penetrates a textile surface and travels through the fibers (Watkins, 1995).

Adsorption – a condition in which liquid does not penetrate a textile's surface, but is attracted to and held against the surface of the fiber (Watkins, 1995).

Air Permeability – a condition in which the velocity of air flow through a textile is measured and expressed in cm^3 of air per cm^2 of fabric per second (ASTM, 1990).

Clo – a unit used to express the thermal insulation required in keeping a sedentary person comfortable at 21°C, where 1 clo = 0.155 $m^2 °C W^{-1}$ (Parsons, 2003).

Clothing Comfort – "a state of satisfaction indicating physiological, social-psychological and physical balance among a person, his/her clothing, and his/her environment." (Branson & Sweeney, 1991, p 99).

Clothing Ventilation – a condition where water vapours and heat escapes through gaps or manufactured openings in the clothing as well as direct penetration of air through clothing (Parsons, 2003).

Comfort – a condition that exists between a person and their environment when there is a mental state of ease or well-being (Sontag, 1985-86).

Conduction – a mode of heat transfer where heat in a stationary substance with a higher temperature moves to another stationary substance with a lower temperature through the interaction of free electrons and molecules (Song, 2003).

Convection – a mode of heat transfer between the air and the surface of the skin as a result of air motion (Gonzalez, Bernard, Carroll, Bryner & Zeigler, 2006).

Dry Thermal Resistance (R_t or R_{ct}) – "Temperature difference between the two faces of a material divided by the resultant heat flux per unit area in the direction of the gradient. The dry heat flux may consist of one or more conductive, convective, and radiant components" (ISO 11092, 1993).

Evaporation – a mode of moisture/heat transfer that is similar to convection but also requires an initial change of state from liquid to vapour (Parsons, 2003).

Exertional Heat Illness (EHI) – a severe condition suffered by soldiers due to physical activity in high temperatures (O'Brien, McPherson, Alsip, & Sawka, 2003).

Fit – a relationship between the human body and the garment (Watkins, 1995).

Garment impediment – a condition that occurs when garments interfere with a person's ability to function (Adams, Slocum, & Keyserling, 1994).

Fragments – flying material that erupts from an explosive device or the wreckage that shatters due to the explosion (Watkins, 1995).

Heat strain – a physiological response that occurs when an individual becomes too hot and the body is unable to transfer heat to the surrounding environment (Levine, Sawka, & Gonzalez, 1998).

Heat stress – a physiological response that occurs when there are environmental parameters that may cause the stressed individual to store heat (Levine, et al., 1998).

Heat transfer – a method through which energy is transported; commonly referred to as: conduction, radiation and convection (Parsons, 2003).

Hydrophilic Fibers – fibers that rapidly absorb water (Conway, 1997).

Hydrophobic Fibers – fibers that have little to no attraction for water and resist absorbing water (Conway, 1997, p 97).

Insulation – refers to a structure of fibers, fabrics or layers of fabric that retains heat within a structure or prevents the permeation of external heat sources (SGMA, 1997).

Mobility – the ease with which a body is able to move within a clothing system (Kreighbaum & Barthels, 1985).

Moisture Permeability Index (i_m) – "the ratio of the actual evaporative heat flow capability between the skin and the environment to the sensible heat flow capability as compared to the Lewis ratio $(1/I_{ea})/(1/I_a)$, no radiation" (Parsons, 2003).

Permeability – a fabric quality that determines how much moisture, air or vapour is allowed to pass through fibers or layers (SGMA, 1997).

Physical comfort – "a mental state of physical well-being expressive of satisfaction with physical attributes of a garment such as air, moisture, and heat transfer properties, mechanical properties such as elasticity and flexibility, bulk, weight, texture, and construction" (Sontag, 1985-86, p 10).

Protective – refers to the capacity to limit injury from exterior objects (ASTM, 1990).

R_{cl} – intrinsic clothing insulation (EC·m^2/Watts) (ASTM, 2005).

R_{ecl} – intrinsic evaporative resistance of the clothing ensemble (kPa·m^2/Watts) (ASTM, 2005)

Radiation – a mode of heat transfer through electromagnetic waves (Parsons, 2003).

Textile – refers to fibers, yarns, fabrics, or products made from these items (Kadolph, 2007).

Thermal Comfort – the state of mind in which the thermal environment is satisfactory (Fanger, 1981).

Thermal transmittance – refers to the amount of heat conveyed between two environments (Collier & Epps, 1999).

Total thermal insulation – refers to the total insulation provided by the garment, including the still air surrounding the body and the garment (Richards & McCullough, 2005).

Water-vapour resistance (R_{et}) – "the vapour pressure difference per unit times rate of water vapour steady-state flow through a unit area, normal to specific parallel surfaces. Water-vapour pressure difference between the two faces of a material divided by the resultant evaporative heat flux per unit area in the direction of the gradient. The evaporative heat flux may consist of both diffusive and convective components." (ISO 11092, 1993).

Wicking – refers to the function of moving liquid along the surface of a fiber (Fourt & Hollies, 1970).

CHAPTER II

REVIEW OF LITERATURE

Valuable information about the thermal comfort properties of clothing systems is garnered for the clothing industry through the use of sweating thermal manikins (Celcar, Meinander, & Gersak, 2008). Clothing is a person's most intimate environment and acts as a key barrier to heat transfer between the human body and its surroundings (Qian & Fan, 2006; McCullough, 2001; Holmer & Nilsson, 1995; Watkins, 1995). We measure thermal comfort to be able to predict whether a garment or ensemble will allow the human body to function effectively in a given environment. Researchers agree that wearing heavy protective clothing, such as body armor, is associated with an increase in the temperature within the micro-environment created by the clothing systems and with a rise in the ambient environmental temperature (Endrusick, Berglund, Gonzalez, Gallimore, & Zheng, 2006; Gonzalez, Berglund, Kolka, & Endrusick, 2006; Qian & Fan, 2006). The protective clothing systems worn by soldiers, including their body armor, contributes significantly to the heat load by insulating the body and reducing heat transfer. The review of literature in this study describes factors related to the person and clothing, including: heat transfer modes, effects of textiles on moisture transfer, body armor, development of QuadGard™ arm and limb protective systems at Oklahoma State University, thermal measurement, and thermal manikins.

As early as the 1960's, scientists and military personnel were calling for the need to lighten the soldier's load. However, Goldman realized that lightening the weight of the armor would solve only part of the problem, because it plays a less important role than the impermeability of the armor, and any weight reduction in the armor would be replaced by additional weights of water and\or ammunition to be carried (2006). Today's soldier carries approximately 90 lbs., with 37 of that 90 coming from the body armor that is designed to protect that soldier (Dillow, 2006, Emery, 2005, U.S. Army Soldier & Biological Chemical Command, 2001). Design criteria of ballistic protective clothing ensembles for the soldier (provide increased ballistic protection and range of motion, extend ballistic protection to the limbs, be modular in style, and reduce ensemble weight, the perception of weight, and thermal stress to the body) are contradictory in nature. The ideal protective clothing system for the military would provide protection from the combative environment while supporting the physical well being of the soldier in extreme temperatures, humidity, and terrain.

Fundamentals of Heat and Moisture Transfer

Heat Balance and the Human Body

The human body attempts to maintain a thermal balance between itself and the environment by producing or releasing heat in specific ways. The human body either absorbs heat from the environment or acts as a heat-producing engine through the processing or burning of food and drink. Havenith states that the human body produces heat due to metabolic reactions that take place within the body (2002). The first law of thermodynamics states that the change in internal energy of a system is equal to the heat added to the system minus the work done by the system (Parsons, 2003). In other words, a balance is required between the work done by the body, its metabolism and exchange of heat with the environment. This concept may be expressed by the following basic equation:

$$M - W = E + C + R + K + S$$

where M is the metabolism or rate of heat production, W is the amount of expended mechanical work, E is the heat lost by evaporation, C is the heat exchanged by convection, R is the heat exchanged by radiation, K is the heat loss by conduction, and S is the rate of body heat stored (Clark & Edholm, 1985). "The second law of thermodynamics states that heat flows spontaneously from a hot body to a cold one but not the reverse (Parsons, 2003, p 478)." In other words, heat from a warm body will flow into a cooler surrounding environment in an attempt to balance the temperature where two different temperatures are involved.

Researchers agree that there are several equations that estimate the heat balance, all based closely on the principle that heat storage is equal to the metabolic heat produced plus or minus all other factors that contribute to heat loss or gain (Barker, Kini, & Bernard, 1999; Cheuvront & Haymes, 2001). For the body to feel comfortable and function properly it must maintain an optimum internal working temperature of 98.6 °F. According to Parson, the surface (skin) temperature is lower than the internal temperature usually 93 to 94°F (2003). Due to the laws of thermodynamics it is understood that if a human body has an internal body temperature of 98.6°F and a surface temperature of less than that, heat will flow from the body into the surrounding environment, as long as the heat transfer is not impeded by insulative clothing or some other impediment. Heat exchange from the skin or clothing surface to the environment is a vital part of the human thermal regulatory process; this energy exchange may take place by conduction, convection, radiation and evaporation (Parsons, 2003; Havenith, 2002; Cheuvront & Haymes, 2001; Barker, et al., 1999; Clark & Edholm, 1985).

Conduction

Conduction of heat in static substances occurs by the interaction of free electrons (solids) and molecules (liquids and gases) causing the transfer of kinetic energy from high to lower temperatures (Song, 2003). For conduction to occur there must be direct physical contact. In other words, if direct contact occurs and there is a temperature difference, there will be conduction of the harm heat to the cooler object. It is logical to assume that the more contact there is, the more conduction can occur. An example of conduction is the transfer of body heat when contact is made with another material or medium, such as cold surfaces. A study on the transfer of heat and moisture through nonwoven fabrics found that conduction is the dominant mechanism of heat transfer through most non-woven fabrics (Woo, Shalev, & Barker, 1994).

Convection

Convection requires material transfer. In other words, liquids or gases mix, and heat exchange occurs as warm and cold particles integrate. Natural convection occurs due to buoyancy forces resulting from temperature differences, e.g. warm air rises (Parsons, 2003, p. 481). Forced convection is a result of a positive displacement of fluid produced by mechanical means, for example adding cold water to a sink full of hot water to reduce the temperature. The greater the temperature difference between the two liquids or gases being mixed, the more rapid the heat exchanges (Watkins, 1995). Clothing serves as an insulator with the outer surface forming the boundary from which heat exchange occurs. It is understood that clothing may hamper convective heat transfer (Craven & Settles, 2006).

Evaporation

Evaporation is an important thermoregulatory mechanism, which relies on heat being taken up by a liquid (e.g. water) when it transforms into vapour and concurrently cools the human body (Song, 2003). Since this heat loss can occur in higher temperatures, evaporation can often be the dominating factor in maintaining overall heat balance because the human body can regulate sweat output within wide limits, particularly in strenuous exercise or in hot environmental conditions. The driving force for evaporation from skin can be expressed as:

$$L_{evap} = m \cdot A \cdot = (p_s - p_a)$$

where m is the permeation coefficient of clothing, A is the surface area; p_s is partial water vapour pressure at skin temperature; p_a is the partial water vapour pressure at ambient temperature (Song, 2003).

High relative humidity will slow the ability of the body to lose heat by evaporation because the air is already holding a great deal of water vapour or moisture, and it is difficult for the air to absorb more. When the relative humidity is low, the dry air absorbs moisture off the skin at a high rate through radiation and convection. Therefore, radiation is another important avenue for heat transfer.

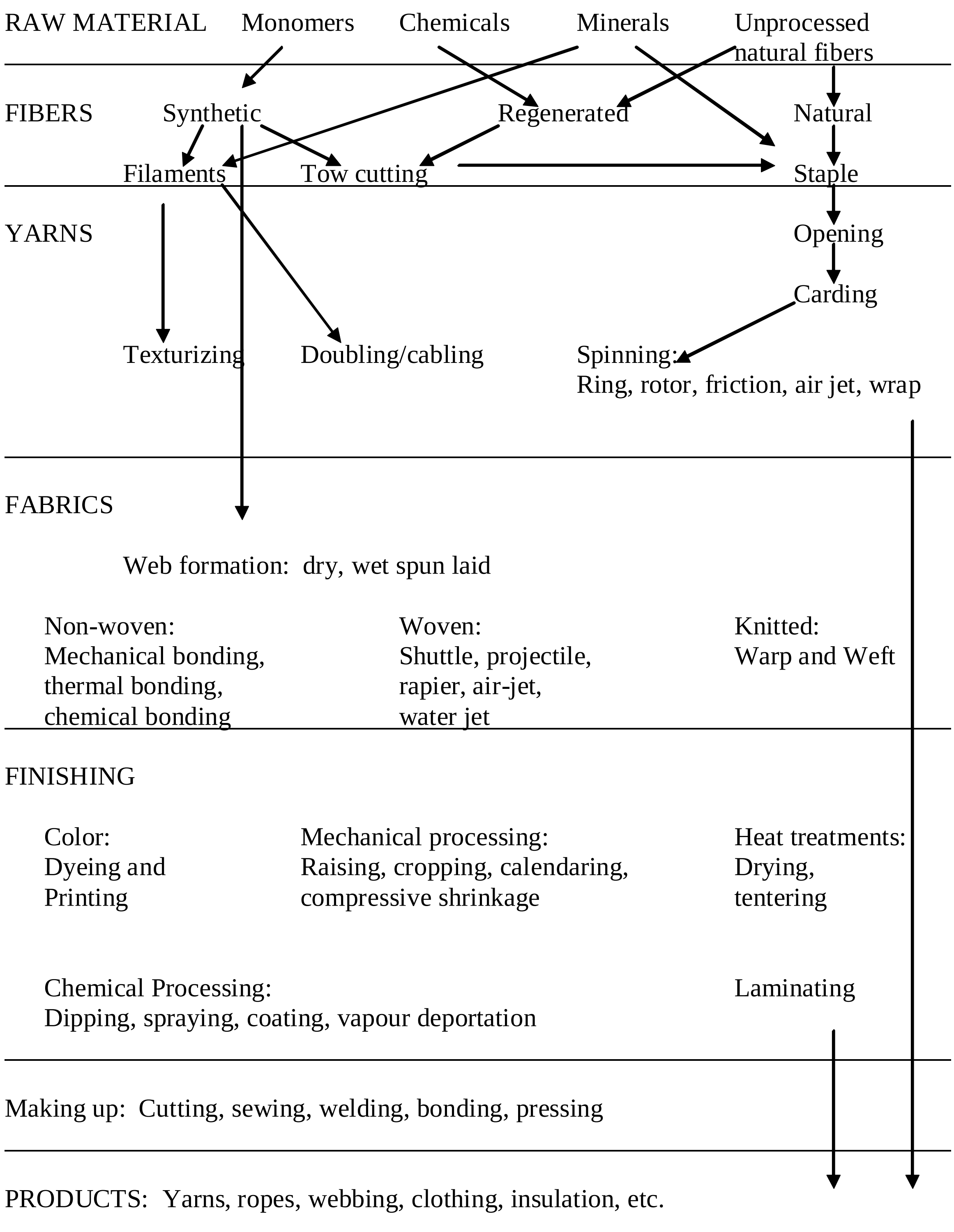
Radiation

Radiation involves the transfer of heat by electromagnetic waves. Electromagnetic waves are the result of the interaction between an electric field and a magnetic field as they move through space. According to Watkins, two types of radiant energy are important to the study of thermal balance, the short wavelength radiation emitted by objects such as the sun, and the long wavelength or infrared radiation given off by the body and other objects in its surroundings (1995). The radiant heat received from the sun is a familiar source of heat. It is important to understand that all objects radiate electromagnetic waves in proportion to their temperatures.

Effect of Textiles on Heat Transfer

As discussed earlier, it is understood that textiles and/or clothing fashioned from textiles can either impede or facilitate the transportation of heat from one environment to another. Bouskill, Havenith, Kuklane, Parsons, & Withey indicate that air layers trapped by textiles contribute to the thermal insulation of a garment (2002). Air transfer between the external environment and the trapped air within the clothing system changes the thermal insulation and water vapour resistance of the clothing system (Bouskill, et al., 2002). Havenith indicates that textiles form a clothing system that creates a boundary between the micro-environment immediately surrounding the body and the larger environment outside of the clothing system (1999). Textiles may be constructed from one or more of the following: fibers, yarns, fabrics, films, or products made of fibers, yarns, or fabrics. Figure 1 is model created by Potluri and Needham to demonstrate the complex relationship involved in the construction of textiles (2005).

Figure 1. Summary of the Hierarchy and Principal Processes of Fiber Assemblies



Potluri, P., Needham, P. (2005, p 152)

The effect that fabric properties have on heat transfer often involves a combination of these components as well as how the fabric is constructed and finished. While examining the influence of air permeability on heat and water vapour transport through woven and nonwovens fabrics, Gibson found that air permeability of fabric becomes important especially when there is air space between fabric and a human body (1993). The amount of open space within a textile structure is very important (Havenith, 1999; Holcombe, 1986). The real thermal insulator of a garment is not the fibers and yarns, it is the still air locked within them. Therefore, the higher the volume of air within a textile structure, the lower the thermal transmittance.

The fiber's physical structure and size, as well as its' chemical composition, affects the overall insulation capacity of a textile. Especially when there are many open areas for air to fill, there is a high surface to volume ratio, and air contributes more than the fibers to thermal resistance (Havenith, 1999). Fibers with crimp, such as wool or textured filament fibers provide more surface area for air to surround increasing their insulation. Today many cold-weather garments are constructed from hollow fibers, which inherently trap air, making the garment lightweight and warm.

Yarn size and structure affects the overall insulation capacity of a textile by impacting the fabric thickness and the amount of air trapped. Spun yarns and bulk-continuous-filament yarns trap more air than fine, smooth filament yarns. The number of plies, along with the degree of twist within a single yarn impacts the thermal insulation capacity of the textile. Yarns with higher twist are more compact, reducing the amount of open space within the yarn; therefore, reducing the yarns' insulative value.

Fabric construction affects the overall insulation capacity of a textile. There are varieties of fabric constructions; foremost are weaving, knitting, and a variety of nonwovens, where there is no processing of fibers into yarns, simply fabrics made directly from fibers or fiber-forming solutions. Most often knits will entrap more air than woven fabrics, although the tightness of the weave or knit is a factor.

Many researchers consider fabric thickness to be of importance and it is often considered to be one of the most important variables in determining thermal insulation, and hence, thermal comfort (Goldman, 2005; Collier & Epps, 1999; Epps & Song, 1992; Holcombe, 1986). It is apparent that a thinner fabric allows more air to escape and that a thicker fabric provides more air space and more resistance to heat transfer that a thin fabric. There is a limit to how thick a fabric can be made and still be comfortably worn; therefore the ratio of thickness to weight is important.

Textured, thick, bulky, tightly-woven fabrics, and fabrics formed with multiple layers reduce conduction. Within the confines of clothing, there is a layer of air surrounding the body and lying between various garment layers that acts as an insulator and impedes heat transfer (Holcombe, 1986). Tightly woven fabrics and designs that reduce air flow control heat transfer by convection, while fabrics with smooth reflective surfaces influence heat transfer by radiation. This is evidenced by the use of lustrous fabrics, often times a satin weave formed with filament fibers, as the lining or back of draperies to aid in the reduction of heat entering the building by reflecting the sun’s rays away from the building (Hammer, 2003).

Effect of Textiles on Moisture Transfer

Where air is a good insulator, the opposite is true of water. The presence of moisture lowers the effectiveness of a structure in preventing heat loss. No matter what form, whether liquid or vapour, moisture enhances heat transfer and reduces the insulative value of a textile (Kuklane, Holmer, & Giesbrecht, 1999). As with many other clothing characteristics, the clothing's ability to move moisture away from the body is largely based on the fiber type, the fiber shape or size, and the fabric construction of the fabric from which the clothing is fashioned. There are three ways in which water can pass through a textile layer: sorption, diffusion, and wicking.

Sorption includes adsorption, absorption, and desorption, where adsorption is the process of taking up water and holding it near the textile' surface, absorption is the process of moisture diffusing throughout the textile, and desorption is the release of moisture from the textile. Absorbency or moisture regain is due to the fiber's chemical composition and amorphous areas, within amorphous areas there is more open space for moisture to fill, thus there is more absorbency. It is an accepted fact that natural fibers are inherently hydrophilic, while synthetic fibers made from petrochemicals are hydrophobic. Although most synthetic fibers are not considered absorbent, the cross-sectional shape and fiber type can influence whether moisture will wick along the fiber's surface. Wicking depends on fiber wettability, as well as the structure of the yarn and fabric. Wicking increases as moisture regain decreases, which is in direct contrast to water vapour dispersion that increases with increased absorbance (Brojeswari, Das, Kothari, Fanguiero, & de Araújo, 2007; Collier & Epps, 1999).

Diffusion as described by Gibson, Rivin, and Kendrick is driven by vapour concentration gradients and involves moisture dispersing through the air spaces between fibers or yarns (2000). How rapidly the moisture disperses depends on the thickness of the textile and to some extent on the construction of the textile (Holcombe, 1986). Moisture will diffuse most quickly through fabrics that are considered to be open weave, possess a low fabric count, or be fashioned from large, bulky yarns. When nonwovens are involved diffusion depends on the size of pores within the fabric structure. Poromeric films are commonly produced using synthetic fibers such as polytetrafluoroethylene (PTFE) or polyurethane (Hostetter, 1998). Gore-Tex® is a brand name for a microporous fabric that is non-permeable and yet breathable. What this means is that the tiny pores within the fabric substrate are so small that larger water drops, such as rain, cannot penetrate the fabric, but smaller water-vapour droplets can escape.

Holcombe explain that when there is sufficient air volume and movement, as well as a low relative humidity, liquid moisture evaporates and rapidly cools the body (1986). Moisture and air movement through a textile fabric are closely related. Air permeability, also known as airflow, is similar to diffusion of moisture vapour through a textile fabric. Fabric porosity is measured by the total volume of void space within a specified area of the fabric (Hsieh, 1995). In other words, as fabric porosity increases, air permeability increases, as does moisture vapour transfer.

Textiles for Body Armor

Textiles for protective clothing, especially impact-protective systems for the military, face a complex set of needs including protection, durability and comfort in a wide range of hostile environments. Two main high performance fibers used in soft body armor are aramid and polyethylene fibers; they are well known for their low density, high strength, and high energy absorption (Lee, Wetzel, & Wagner, 2003; Shishoo, 2002). Some trade names for fabrics made out of aramid fibers include: Kevlar®, Twaron®, and Technora® brands. Aramid is a nylon variant, nylon is a polyamide fiber (aramid is an aromatic polyamide fiber), developed by a DuPont chemist, Stephanie Kwolek, to possess exceptional heat and flame resistance (Selle, 2004). Kevlar®, a high-tenacity para-aramid (4.0-5.3/3.0-4.1 grams/denier), is lightweight (1.38-1.44 grams/cc) and fatigue- and damage-resistant, it is five times stronger than steel on an equal-weight basis, while it is 43 percent lower in density than fiberglass it is used in the construction of boat hulls, skis, spacecraft and aircraft parts (Grujicic, Arakere, He, Gogulapati, & Cheeseman, 2008; Kadolph, 2007). Therefore, garments constructed out of aramid fibers, such as Kevlar®, are relatively lightweight and bullet- and knife-resistant.

Some trade names for fabrics made out of polyethylene fibers include: Dyneema® and Spectra® are based on polyethylene fibers, also known as olefin (Grujicic, et al., 2008; Gadow & von Niessen, 2006). Polyethylene is a simple linear structure of repeating $-CH^2-$ units and is used in ropes, twines, and utility fabrics and is referred to as olefin (Grujicic, et al., 2008; Kadolph, 2007). Dyneema® is manufactured by DSM Dyneema® and is up to fifteen times stronger than quality steel and up to 40 percent stronger than aramid fibers, on a weight-per-weight basis (DSM Dyneema, 2008). The low specific gravity of olefin along with its strength and flexibility provides the wearer with freedom of movement without compromising its protective value. Although olefin is nonabsorbent, it has excellent wicking properties, which makes it desirable for use in some active sportswear, socks, underwear, and as a cover stock in disposable diapers.

Body Armor

It is often said that textiles are used in impact-protective clothing, also called body armor (BA) to protect military personnel, policemen, and others from bullets and fragments. Watkins insists that it is more precise to say that textiles can be used in garments that provide protection from projectiles, but to do so, they must be used in multiple layers (1995). Ballistic material is incorporated into body armor to absorb the pressure from the impacting object and disperse the energy from the impact throughout the ballistic material; much like a sponge absorbs water at one location and spreads the water throughout the sponge. In her book, *Clothing the Portable Environment*, 2nd edition (1995, p 98) Susan Watkins establishes criteria for materials used for impact-protective materials, as follows:

1. *A material should prevent an impacting object from focusing all of its pressure on one small area of the body.*
2. *A material should allow the impacting object or the body to decelerate gradually upon impact.*
3. *A material used on the body should not contribute to an abrupt change in momentum at the moment of collision or immediately after it collides with an impacting object.*
4. *The material should change the kinetic energy of an impacting object into a form of energy less harmful to the body.*
5. *The material should prevent a colliding object from breaking the skin surface or entering the body.*

Watkins further explains that while there are a few materials that fulfill all five criteria, the majority of the materials provide protection in only one or two of the ways identified and must be used with other materials to provide full protection (1995). Therefore, many impact-protective systems are multi-layered and contain a combination of protective materials (Watkins, 1995)

Military and civilian ballistic protection is divided into flexible lightweight, soft body armor and rigid, hard body armor (Gadow & von Niessen, 2006). According to Watkins (1995), rigid materials are usually called armor plates and can be identified as the following three types of materials: 1) metals, including steel, aluminum, and titanium; 2) ceramics, such as aluminum oxide or boron carbide, and 3) fiber-reinforced resins, often called plastics. These stiff fiber-reinforced resins are popular today because of their durability, resistance to electrical conduction, low cost, and the ease with which they can be molded into complex forms (Watkins, 1995). According to Watkins, the fiber-reinforced resins are composed of two substances: a fiber and a resin (synthetic fiber, such as: polyester, nylon, polypropylene, and polycarbonate) that can be molded into a specific shape (1995). However, solid and stiff armor is more likely to be heavier in weight and less flexible, restricting motion.

As discussed earlier, it is well known that many protective ensembles, even brief cases, are constructed out of high-tenacity aramid or polyethylene fibers to protect military personnel, policemen, political candidates, and others from bullets and fragments. Several layers of these light and flexible fabrics made from high-tenacity fibers do not provide sufficient protection against high-speed bullets (Gadow & von Niessen (2006). For protection against this level of threat, hard armor and light ceramic strike-face plates that wear down, dull, and/or splinter armor-piercing rounds are needed (Grujicic, Arakere, He, Gogulapati, & Cheeseman, 2008). The disadvantage of such extreme protection is the increased weight and a concurrent decrease in flexibility (Gadow & von Niessen (2006). Non-ballistic threats such as knives, sharp blades, or sharp-tipped weapons are another common threat that high-tenacity fibers are limited in their level of protection, because the sharp points that are inherent in these potentially lethal weapons are able to penetrate between the weave. According to Gadow & von Niessen, one solution is to add layers of titanium foil or to incorporate special resin-treated fabrics, such as DuPont Kevlar® Comfort AS 299 (2006).

Development of QuadGard™ Arm and Limb Protective Systems

Dr. Donna Branson, Director of the Institute for Protective Apparel Research and Technology at OSU, has led her OSU team in developing several versions of arm and limb body armor designed to specifically protect a soldier's arms, legs and lower back from shrapnel and small arms fire. The following are design requirements identified from the design criteria provided by Army Research Laboratory (ARL), and Naval Research Laboratory (NRL): protect key areas of arms and legs from blast fragments, balance ventilation for cooling relief with protection, wear with existing outer tactical vest (OTV), stay within specified weight constraints, and provide ease of movement, quick and easy donning and doffing (Matic, Hubler, Sprague, Simmonds, Rupert, Bruno, Frost, Branson, Farr, & Peksoz, 2006). Results from combat casualty research, along with considerations about additional weight, determined that QuadGard™ should be able to stop smaller fragments with soft armor at a level slightly below that of the soft OTV (Matic, et al., 2006). Based on the design criteria and requirements, the QuadGard™ arm protectors are sleeves fashioned of layers of puncture and abrasion-resistant materials (Cordura®, Dyneema®, and Rip-stop®) that attach to the OTV by using three straps, one of which connects the arms together across the back. While the QuadGard™ legs are pants also fashioned from layers of puncture and abrasion-resistant materials (Cordura®, Dyneema®, and Rip-stop®) that resemble cowboy chaps held up by suspenders and a belt and cover most of the lower torso, buttocks, hips, and legs. With the 360-degree coverage provided by the QuadGard™ limb body armor, ballistic protection can increase nonlethal and safe operating areas around an IED by reducing the minimum standoff distances from the soldier to the explosive device (Matic, et al., 2006).

Thermal Measurement

Protective clothing systems factor into the heat loss and thermal comfort of the human body by causing or exacerbating heat strain in those wearing them (Levine, et al., 1998, Richards & McCullough, 2005). Researchers agree that the military and civic communities issue clothing systems that are designed to protect against a specific health hazard (e.g., IEDs or fire), which may lead to other health hazards (e.g. heat illness or dehydration). Testing of protective clothing is required to select systems that minimize heat strain for those who must work in protective clothing systems (Levine, et al, 1998). To effectively assess and evaluate such protective clothing systems, body heat balance models and thermal comfort indices have been developed which require values of the thermal insulation and evaporative resistance of clothing. There is a progressive relationship among the tests used for a heat strain evaluation, as each series of tests builds on the previous tests: guarded hot plate for textiles, manikin for clothing systems, prediction model based on manikin and human data, and human laboratory and field tests (Levine, et al., 1998).

Guarded Hot Plate

According to Ralph F. Goldman, evaluations of flat fabrics should be tested on a classic "Cleveland Guarded, heated flat plate", in an environmental controlled chamber with specific air motion over the plate, to measure the Clo value of materials to attain an accurate measurement of specific fabric characteristics (2006). Goldman states that there are five key material properties, which are as follows: 1) fabric insulation, 2) fabric moisture permeability: 3) wicking characteristics, 4) water uptake/holding characteristics, and 5) drying time (2006). Air is the dominant insulator in clothing, contained either in the fibers or between clothing layers (Goldman, 2006; Watkins, 1995).

To effectively evaluate flat textile layers, a thermal hotplate may be used following testing standards, such as IS0 11092 "Textiles – Physiological effects – Measurement of thermal and water-vapour resistance under steady-state conditions", to determine these values (Richards & McCullough, 2005). Textiles are cut into 12 x 12 inch squares (each forming one layer) then placed flat on a temperature-controlled hot plate in an environmental chamber. This procedure is designed to simulate the transfer phenomena that occurs in the micro-climate created between the skin surface, the various textile layers, and the surrounding ambient atmosphere. A benefit of guarded hot plate testing is that it can be used to screen and rank a large number of textiles in a relatively short amount of time. Researchers agree that a limitation of guarded hot plate testing is that the thermal resistance and vapour permeability measured for flat textile samples are not always the same as when the textile is constructed into an ensemble (Goldman, 2006;

Levine, et al., 1998). While the guarded hotplate is effective for testing flat textile layers, it is not as useful in testing clothing systems that cover a human body (Watkins, 1995).

History of Thermal Manikins

For more than 60 years, thermal manikins have served researchers in the evaluation and investigation of thermal transfer associated with clothing, garment ensembles and garment treatments designed to cover the human body and its' complex 3-dimensional form (Holmer, 2004). Thermal manikins were originally designed to investigate the thermal interaction of the human body with its environment, particularly in the design and fabrication of clothing due to their intrinsic thermal properties. The number of manikins being manufactured and used and the organization of international meetings specifically devoted to thermal manikin applications indicate the growing interest in using thermal manikins in research and measurement standards (Holmer, 2004). The first human shaped thermal manikin made for the US Army in the 1940's was a one-segment, construction of electroplated copper, with electrical circuits that uniformly heated the surface (Goldman, 2006; Holmer, 2004; Nilsson, 2004). The demand for more detailed and concise information instigated the construction of manikins with several, independently controlled segments over the body surface. Other materials have been incorporated in the production of modern manikins in the endeavor to attain a more representative measurement associated with the maintenance of heat balance attained by a human body, while reducing cost and weight. Today, the majority of the thermal manikins have more than fifteen segments (Nilsson, 2004). Thermal manikins have evolved from an analogue, one-segment non-movable, copper man to digital, multi-segmented, movable, and articulated, thermal manikins constructed from a variety of materials that provide relevant, reliable and accurate measurements of heat losses of not just flat 12 x 12 sets of layered fabrics, but of three dimensional garment ensembles as they perform on a movable human shape. Thermal manikins can be exposed to extreme conditions under which a human body could not survive. Recent developments of sweating manikins allow more realistic simulations of the human thermal interaction with the environment incorporating a method that is quick, easily standardized and repeatable (Holmer, 2004). Researchers agree that there are two major areas of research for thermal manikins, which include the assessment of heat transfer characteristics and the impact of other thermal environments, including clothing, interiors, sleeping bags, cars, and chairs on the human body (Goldman, 2006; Holmer, 2004; Nilsson, 2004). Manikins are able to test for the following clothing factors: amount of body surface area covered by textiles and the amount of exposed skin, distribution of textile layers and air layers over the body surface (i.e. non-uniform), looseness or tightness of fit, increase in surface area for heat loss (i.e. clothing area factor) due to the textiles around the body, effect of product design, adjustment of garment features (i.e. fasteners open, hood up, etc.), variation in the temperature (and heat flux) on different parts of the body, effect of body position (i.e. standing, sitting, lying down), and effect of body movement (Goldman, 2006; Holmer, 2004).

Thermal Manikin

Thermal manikins measure dry thermal resistance (insulation) and water vapour (evaporative) resistance of clothing systems, as well as other environmental systems, such as automobiles, space shuttles, and buildings. Researchers agree that an increasing number of manikins in operation can simulate human sweating and provide valuable information about heat exchange by evaporation (Qian & Fan, 2006; Fan & Qian, 2004; Nilsson, 2004). According to Zimmerli heated and sweating thermal manikins, both stationary and moving alike, transport heat and water vapour through material and openings and are the best equipped to test physiological properties of all types of protective clothing (2000).

Thermal measurements on complete clothing systems are preferred to small flat textile layers because they reflect the amount of body surface area covered by clothing, the amount of exposed skin, the distribution of garment layers and air layers over the body, effect of body position, body movement, looseness or tightness of fit, the increase in surface area for heat loss, and variations in skin temperature on different parts of the body (McCullough, 1993). Holmer and Nilsson add that "measurements on whole ensembles are required to account for: whole-body heat exchange, three-dimensional effects; layer effects; size, drape and fit; body coverage; and dynamic effects (1995, p. 809)." Holmer and Nilsson caution and emphasize that, although measurements on manikins are: realistic and objective; quick, accurate and reproducible; cost-effective; and provide baseline values for use in standards and prediction models, the relevance of manikin measurements relies greatly upon the validation in wearing trials with subjects (1995). In agreement with this premise, McCullough stresses that thermal manikins do not simulate the human body physiologically, they are simply thermal measuring devices in the size and shape of a human being that are heated so that their surface temperatures simulate the local mean skin temperature of a human being (2005b).

Walter – Sweating Thermal Manikin

"Walter" is a sweating thermal manikin, created by Dr. Jintu Fan's team from Hong Kong Polytechnic University to simulate perspiration using a waterproof, but moisture-permeable, fabric "skin" and measures thermal insulation (R_t or R_{ct}) and moisture-vapour resistance (R_{et}). Dr. Fan explains that unlike other thermal manikins, which are fashioned from more structural components than mostly water and high strength breathable fabric, water in the fully filled body of Walter maintains the body shape, skin temperature and the water evaporation from the skin (2006a). Walter stands 5' 8" tall, has the stature of a small man (neck = 18 in., chest = 38 in., waist = 35 in., and hip = 38.5in.) along with articulated arms and legs that are motorized to simulate walking from 0 to 4 km/hr (Fan, 2006c). Similar to the human body's blood circulation system, Walter has a water circulation system that distributes the heat produced in the core region of the head, arms and legs (Fan, 2006a).

To explore ways to improve the finishing process, Walter has been used by a garment manufacturer to compare the comfort properties of T-shirts having different finishing treatments or materials (Fan, 2006b). According to Dr. Jintu Fan, the manufacturer found that their Teflon finished cotton T-shirts tended to have lower moisture vapour resistance than cotton t-shirts with nano-care and wrinkle-free finishes (2006b). Two other examples of Walter's application, provided by Dr. Fan, are as follows:

1) compare the performance of two army uniforms, where the only difference between the two designs was the fabrication,

2) compare the performance of two traditional designs of firefighter turnout gear, where the only difference between the two designs was the construction of the insulation layers (2006b).

Thermal Manikin Studies

Much like the soldier, firefighters must wear heavy protective clothing ensembles to protect them from the environments that they fight. An important means of body heat loss when a person is physically active or in a hot environment is the evaporation of sweat. In 2007, a study was published in the *Textile Research Journal* delineating methodology developed by Jun Li, Roger L. Barker, and A. Shawn Deaton to assess quantitatively the effects of clothing factors on heat and moisture transfer performance of firefighter turnout gear. In an environmental chamber (set as T = 25°C, RH = 65%, and wind velocity = 1.0 m/s, flowing steadily from the chamber roof), a sweating manikin (heated to keep 35°C mean skin temperature with a sweating rate set at 200 g/m^2 to keep the manikin surface moist) was used to differentiate the effects of clothing factors, focusing on fabrication and design features, on heat and moisture transfer performance of firefighter turnout clothing systems (Li, Barker, & Deaton, 2007).

To study thermal insulation and moisture permeability of firefighter turnout clothing systems material components and design features were varied. Along with varying the textile and design features, two new indices were studied through the manipulation of the openings of the firefighter turnout gear at the neck, wrists, waist, and ankles by leaving open or by sealing. In their 2007 study, Li, Barker & Deaton introduced two new indices: CI_t and Ci_m. They were proposed to evaluate heat and moisture transfer capabilities of firefighter turnout clothing systems, which were defined as the changing rates of I_t and i_m from conditions that feature the clothing openings fastened in a regular fashion and these same openings fastened in the regular sense, as well as being sealed closed (Li, Barker, & Deaton, 2007).

Three variables studied were determined by the standard three-layer fabrication of the firefighter turnout gear and are as follows: 1) the outer shell, 2) the moisture barrier, and 3) the thermal liner. Another three variables were selected from basic design features of the firefighter turnout clothing system and are as follows: 4) design/style, 5) size/fit, and 6) accessory.

Using these variables, eleven different firefighter turnout clothing systems with nine different material systems were tested by the aforementioned sweating manikin, dressed in garments typically worn by firefighters, including boots, helmet, gloves, and a self-contained breathing apparatus (SCBA), housed in an environmental chamber located in the Textile Protection and Comfort Center of North Carolina State University (Li, et al., 2007). The testing environment was set to simulate firefighters' mild working conditions.

The manikin testing results of each ensemble was recorded as an average of three independent replications and SAS Fisher's LSD tests were used to analyze the data (Li, et al., 2007). Thermal insulation (I_t) increased significantly (confidence level a = 0.05) in the test garments with sealed openings, while i_m decreased significantly (a = 0.05), than with unsealed openings (Li, et al., 2007). In addition, the researchers indicated that the test garments did not fit the manikin tightly; therefore, convection existed within the air trapped between the skin and the inner thermal liner. Encumbering heat loss was the main effect found from sealing the openings (Li, et al., 2007). This raises the question whether the ventilation features built into the QuadGard™ body armor systems actually ventilate the body.

Garment design and fit are important since ventilative heat and moisture transfer take place through the openings of the clothing system (Qian, 2005). Based on the results of this study, it is feasible that a similar study will differentiate the effects of clothing factors on heat and moisture transfer performance of the three different QuadGard™ body armor systems, especially since the three designs differ in the amount of coverage and ventilation provided. Continuing with this vein of thought, the following study focuses on style/design features.

Kathy K. Mullet and Hsiou-Lien Chen, Oregon State University, conducted a study to determine whether different sleeve designs affect the total garment thermal insulation value by examining the effect of three different sleeve structures using a standing, 26 zone Newton sweating thermal manikin (2006). Construction and fabrication of the three garment treatments were held constant; the only difference was the design of the sleeves at the shoulder area. The three different sleeve styles studied were set-in, kimono, and raglan. To assure the same size and fit for each garment, a basic torso and set-in sleeve pattern were drafted to fit that specific manikin's body measurements (Mullet & Chen, 2006).

Reliability was attained by testing each garment treatment, in a controlled environment of room temperature 20.5°C and 58% relative humidity on a sweating manikin with a core body temperature set at 34°C, three different times for three hours each (Mullet, et al., 2006). Thermal resistance data (watts/metre^2) were collected and recorded by sensors located at eight different areas of the arms and torso of the manikin

(Mullet, et al., 2006). Due to the differences in shape, the total surface area was used to compare the sleeves, because the same basic patterns were used to create all sleeves. Therefore, garment clo value was recorded by the manikin as the total watts expended based on the surface area covered by the garment (Mullet, et al., 2006).

Since the total surface area covered by each garment was different, set-in sleeve (0.980 m^2), kimono sleeve (0.992 m^2), and raglan sleeve (1.057 m^2), it is not surprising that the overall clo values for the three different garment treatments were different (Mullet, et al., 2006). The surface area of the set-in sleeve garment was the smallest, with the closest fit to the body, which was verified by the smallest clo value of 1.44. The total clo value for each total garment are as follows: set-in sleeve (1.44 clo), kimono sleeve (1.53 clo), and raglan sleeve (1.63 clo).

All factors such as material and environment were controlled; in this study, the only variable changed was the design of the garment sleeve (Mullet, et al., 2006). The results from this study by Mullet & Chen indicate that the surface area of the garment is related to the clo value (2006). Other studies have shown that the fit of the garment can affect the total insulation value of the garment, but this study (where the differences between the clo values are attributed to the differences in the sleeve structure and not just fit) indicate that fit is related to the garment design as well (Mullet, et al., 2006). Therefore, it is conceivable that the differences in design features of the three different QuadGard™ systems will affect their heat and moisture transfer performance.

Researchers continue to study different material components and design features affect on heat and moisture transfer including the addition of spacer fabrics or garments constructed with spacer fabrics. One idea is to add "space" between the clothing systems and the human body to promote the transfer of heat and moisture from the body, which leads to the following study.

Endrusick, Berglund, Gonzalez, Gallimore, and Zheng conducted a study to determine if the use of a spacer vest, designed to enlarge the space between the soldier's body and the Interceptor Body Armor (IBA) currently worn by U.S. military forces, actually enhances the potential for evaporative cooling (2006). This research team hypothesized that an increase in evaporative cooling could reduce overall sweat rate and consequent soldier dehydration. This hypothesis was based on Goldman's seminal work in 1969, where Goldman found that wearing body armor in humid environments increased the temperature around the wearer by about four centigrade degrees (Endrusick, et al., 2006; Goldman, 1969). The team tested seven lightweight, 1 centimeter thick spacer vests for thermal insulation (clo) and water vapour permeability (i_m) on a sweating thermal manikin. Endrusick, et al., (2006) indicate that

> thermal insulation represents the total resistance to dry heat transfer between the skin's surface and the ambient environment. Water vapour permeability is the total conductance for latent heat transfer between the skin and environment. Both properties are functions of wind speed with increased air velocity resulting in lower thermal insulation (clo) and higher water vapour permeability (i_m) measurements (p. 382).

A sweating thermal manikin was dressed in three different garment treatments: 1) with the U.S. Army Temperate Battle Dress Uniform (TBDU); 2) with the IBA over the TBDU; and 3) with the IBA over the various spacer vests and the TBDU (Endrusick, et al., 2006). The protocol was designed to determine if there was any difference between a separate, stand-alone spacer vest and spacer, fabric permanently integrated into the inner lining of the body armor, as well as between two different types of spacer material construction: an open mesh style and a waffle style with indented dimples (Endrusick, et al., 2006).

Furthermore, results from the thermal manikin were entered into a computer model program to predict core temperature, skin temperature, heart rate, sweat rate, skin wettedness, and total body water loss. A typical soldier's (70 kg, 1.7 m tall) human responses were downloaded to simulate the thermo-physiological results to the addition of a spacer vest under the IBA (Endrusick, et al., 2006). With the computer model, the team was able to specify energy expenditure by choosing an activity to be simulated, the duration of the activity, and to select specific environments in which to be exposed. In the case of this study, the model simulated repeated, intermittent exercise (10 minutes rest/30 minutes walk) with exposure to hot, dry environments with air temperatures of 30, 40 and 50˚C (Endrusick, et al., 2006).

Results from the thermal manikin tests indicated that when the spacer vest was worn between the IBA and TBDU, thermal insulation was reduced and water vapour permeability increased; whereas, when the IBA was worn over the TBDU thermal insulation increased and water vapour permeability decreased (Endrusick, et al., 2006). Endrusick states that

> these results translate into a theoretical increase in whole body evaporative cooling potential (i_m/clo) of approximately 20% when wearing a spacer vest compared to when wearing the IBA without a SV. Predictive model results showed thermo-physiological benefits when using a spacer vest with lower skin wettedness

at 30˚C, lower core temperature, skin temperature, heart rate, sweat rate, skin wettedness, and total body water loss at 40˚C and lower core temperature at 50˚C (p. 381).

The use of spacer fabrics was conceptualized to provide a continuous air channel surrounding the torso between the TBDU and the entire inner surface of the IBA. These positive results indicate that the use of spacer vests reduced the inherent thermal and evaporative resistance of the IBA and promote continuing research and development in this area (Endrusick, et al., 2006).

The addition of spacer fabrics created positive results; another aspect would be to incorporate microencapsulated phase-change materials (PCMs) in the design. Instead of adding an additional spacer garment, garments could be constructed out of materials containing microencapsulated phase-change materials and compared with garment constructed with standard fabrication to investigate if these different fabrics have an affect on heat and moisture transfer. With this in mind, it would be interesting to compare heat and moisture transfer components of garments made from microencapsulated phase-change materials (PCMs) with the same garments constructed from standard fabrics without phase-change materials.

One such study investigates the thermal comfort properties of different male business clothing systems on water vapour transmission (WVT) and thermal insulation (I_t) using a sweating thermal manikin Coppelius (Celcar, et al., 2008). Ten different combinations of male business clothing systems were tested under three ambient conditions (10˚C/50% RH, 25˚C/50 % RH, and -5˚C) and two sweating levels: 0 and 50 gm $^{-2}$h^{-1} sweating levels (Celcar, et al., 2008). The following standardized test methods were used to test different materials prior to manufacturing the suits to be tested: thermal resistance (R_{ct}), WVT: Gore cup method modified by Gore-Tex (Gohlke, 1980), air permeability, thickness, and mass per unit area (Celcar, et al., 2008).

In calculating moisture retention, Celcar, et al., (2008) used the following:

where m_s is the water fed into the manikin (g), m_c is the condensed water in the clothing (g), m_e is the evaporated water (g), and φ is the specific heat of evaporation for water (0.674 Wg^{-1} at 25°C).

The amount of evaporated water M_e as a percentage of the water input, giving a value for the WVT of the test clothing systems. M_e is calculated by:

$$M_e = \frac{m_e}{m_s} \cdot 100 \text{ per cent. (p. 245)}$$

A selection of the clothing systems were constructed out of standard suit fabrics while others were constructed out of clothing materials containing microencapsulated phase-change materials (PCMs) in the liner and outerwear material. The first phase tested five three-layer clothing ensembles (underwear, shirt, and suit with liner) at 10°C at 50% RH and 25°C at 50 % RH with, 0 and 50 g/m^2h sweating levels. The second phase, tested five four-layer clothing ensembles (underwear, shirt, suit with liner, and coat with liner) at 10°C at 50% RH and -5°C with, 0 and 50 g/m^2h sweating levels (Celcar, et al., 2008).

The researchers indicated that weighing each garment before and immediately after the test determined the amount of that water accumulated in the clothing, due to the water content in the air, which evaporated throughout the clothing and condensed in each piece of clothing (Celcar, et al., 2008). In this study, the coat absorbed more water in the cold condition of -5°C ambient temperature than the other individual pieces.

Results of dry tests revealed that heat loss was 60% higher at 10°C than at 25°C, which means that the manikin expended more energy to maintain an average skin temperature of 34°C at an ambient temperature of 10°C than at an ambient temperature of 25°C (Celcar, et al., 2008). Dry heat losses in cold conditions, with an ambient temperature of -5°C were 48 % higher than at an ambient temperature of 10°C. The researchers compared dry heat losses at 10°C for all combinations of male business clothing systems; three-layer systems compared with four-layer systems, and found that the manikin required more heat to maintain the average skin temperature with three-layered clothing systems than with four-layered systems. It seems obvious that three-layer clothing systems would have lower insulative value than four-layer clothing systems and the results support this. Small differences in heat loss and thermal insulation were found to exist between clothing systems with and without PCM particles. For example, combination cs1, male suit with CV liner revealed a small reduction in thermal insulation than the same combination cs5, male suit with CV liner and PCM particles attributed to higher levels of dry heat loss (Celcar, et al., 2008). The researchers explained that the difference between these thermal insulation values was most likely due to the difference in thickness and weight of liner materials with and without PCM particles (Celcar, et al., 2008).

When comparing evaporative heat losses it was noted that there were very small differences between the thermal insulative values at different ambient temperatures, as well as small differences between clothing systems made of materials with PCMs and standard wool materials (Celcar, et al., 2008). The researchers could not confirm that differences were due to the content of PCM particles and indicated the need for further research to investigate the differences (Celcar, et al., 2008).

In summary, thermal balance may be impaired or enhanced depending on the fiber content, design and construction of clothing systems. Well known modes of heat transfer through clothing are conduction, convection, radiation, and evaporation. There are two types of body armor: rigid and soft. Rigid body armor is constructed using ceramic plates, while soft body armor is formed through the layering of fabrics constructed from high performance fibers. While, a guarded hot plate is recommended to test flat fabrics and simple layers of fabrics, a thermal manikin is recommended to test the complex 3-dimensional form of clothing ensembles. To be able to identify textile fabrics and design features that optimize the thermal comfort of clothing ensembles, the complete ensemble should be evaluated using a thermal manikin. Studies found that fabrication, use of additional spacer fabrics, design features, and garment fit could affect the heat and moisture transfer performance of clothing systems. Other research studies found that dry thermal resistance and water vapour resistance are correlated with the number of layers of fabrics used, the amount of air within the fabric and the type of finish applied to the fabric of specific garment ensembles.

CHAPTER III

METHODOLOGY

This study was conducted in two phases to investigate the differences in intrinsic clothing insulation and intrinsic clothing evaporative resistance as measured by a sweating manikin between three different QuadGard™ body armor systems identified as: QuadGard™ II (QG II), QuadGard™ IV (QG IV), and QuadGard™ V (QG V). Differences between two types of ballistic materials on intrinsic clothing insulation and intrinsic clothing evaporative resistance using a sweating manikin were also investigated. This chapter provides information on the independent variables, dependent variables, equipment, test protocol, and both phases of the study with their experimental designs and statistical analyses.

Independent Variables

Armor System

Armor system was the first independent variable. Levels for Phase 1 included: QuadGard™ II, QuadGard™ IV Ventilated, and QuadGard™ IV Not Ventilated. Levels for Phase 2 included: QuadGard™ V and four modular configurations: QuadGard™ V Arms, QuadGard™ V Legs, QuadGard™ V Upper Arms, and QuadGard™ V Upper Legs. The standard ensemble used beneath all treatments consisted of the BDU jacket, BDU pants, and the standard Interceptor vest composed of Kevlar® without hard plates. All three QuadGard™ armor systems were constructed from identical military specified fabrics. Cordura®, a nylon fabric that is well known for its durability and high abrasion resistance, was used for the outer layer of the shell. Rip-stop®, a nylon filament-yarn fabric with slightly larger warp and filling yarns appearing at regular intervals to create a grid within the fabric, was used for the inner layer of the shell.

Design criteria used for the development of QuadGard™ was provided by the Naval Research Laboratory (NRL) and was based on combat casualty data. First, Level II protection (9 mm handgun threats and fragment protection), of vulnerable areas of the body such as nerve and vascular bundles that are concentrated near the surface of the body, the sciatic nerve in the lower back and buttocks, femoral arteries in the lower abdomen, and joints where prognosis for full recovery from injury is poor was foremost. Second, compatibility with the existing outer tactical Interceptor vest assured potential for immediate utilization. Third, flexibility, minimal thermal discomfort and weight, ease of movement, and rapid donning and doffing. System development which began in May 2004, chronicled in several sources (Peksoz, Branson, & Farr, 2007; Matic, et al., 2006; Branson, Peksoz, Ricord, Farr, & Kumphai, 2006), resulted in the utilization of QuadGard™ Armor Systems IV and V units for use by U. S. Marines in Iraq and Afghanistan.

Features common to all QuadGard™ Armor Systems are as follows: three-piece arm/shoulder unit, openings or mesh to accommodate passive ventilation, shaped ballistic inserts for fit and mobility, suspenders, and long, side leg zippers for ease in donning and doffing. Figure 2 provides a visual overview of all three QuadGard™ systems.

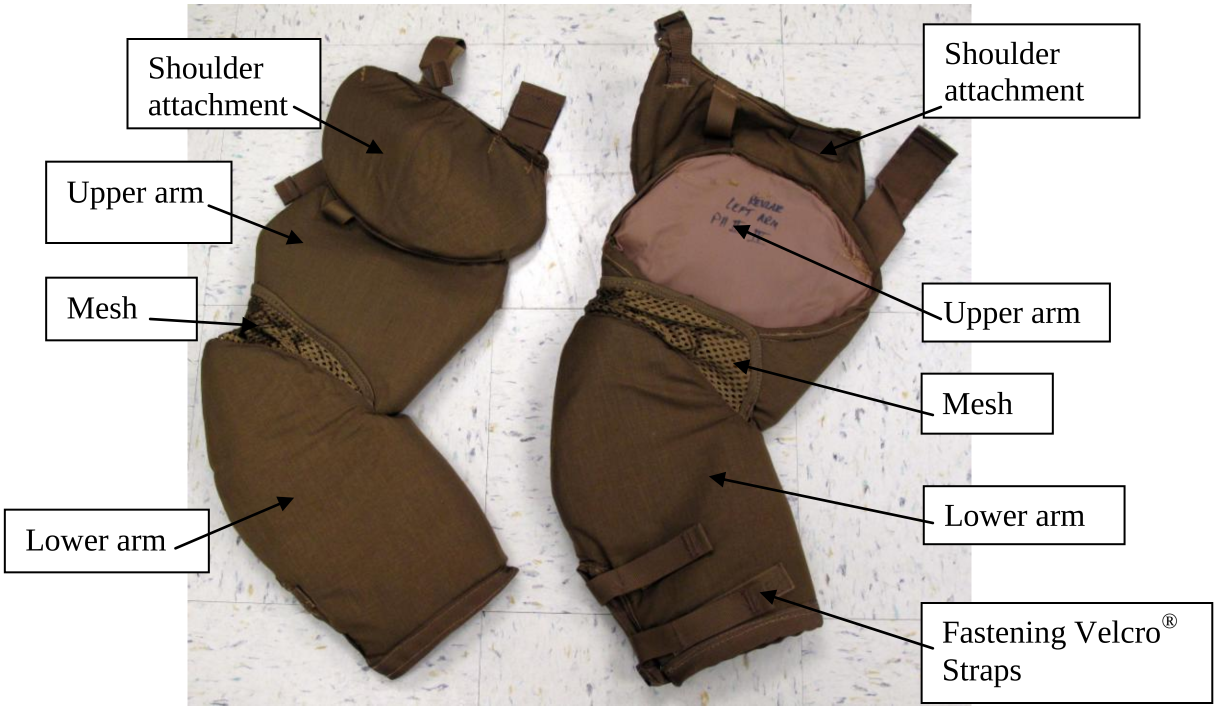
Figure 2. QuadGard™ Armor Systems

QuadGard™ II QuadGard™ IV QuadGard™ V

QuadGard™ II Armor System

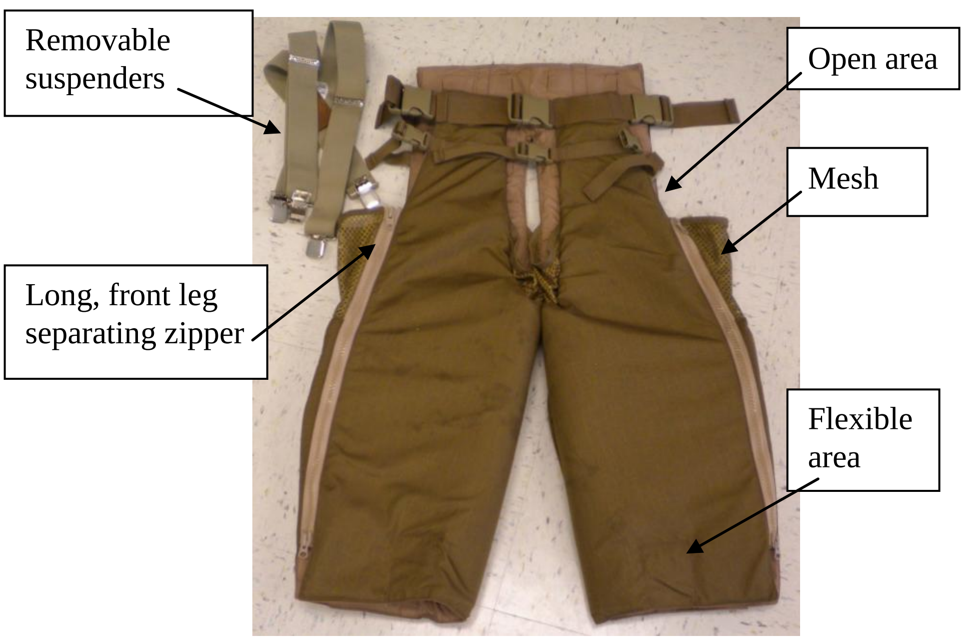
Figures 3 and 4 provide a more complete illustration of QuadGard™ II that consists of sewn-in ballistic material and a three-piece arm unit that is sewn together and cannot readily be disassembled. The leg unit has a large portion of the outside upper leg open or covered with mesh, i.e., no ballistic protection provided. QuadGard™ II balanced the contradictory and conflicting design criteria for achieving protection and minimizing weight through the use of 'body shadowing' by leaving interior surfaces open that were generally protected by another body part depending on position, e.g., underarm area was not covered by armor because it is often covered by the arm when held normally at the side of the body.

Figure 3. QuadGard™ II Arm System



QG II Arm Front QG II Arm Back

Figure 4. QuadGard™ II Pant Systems

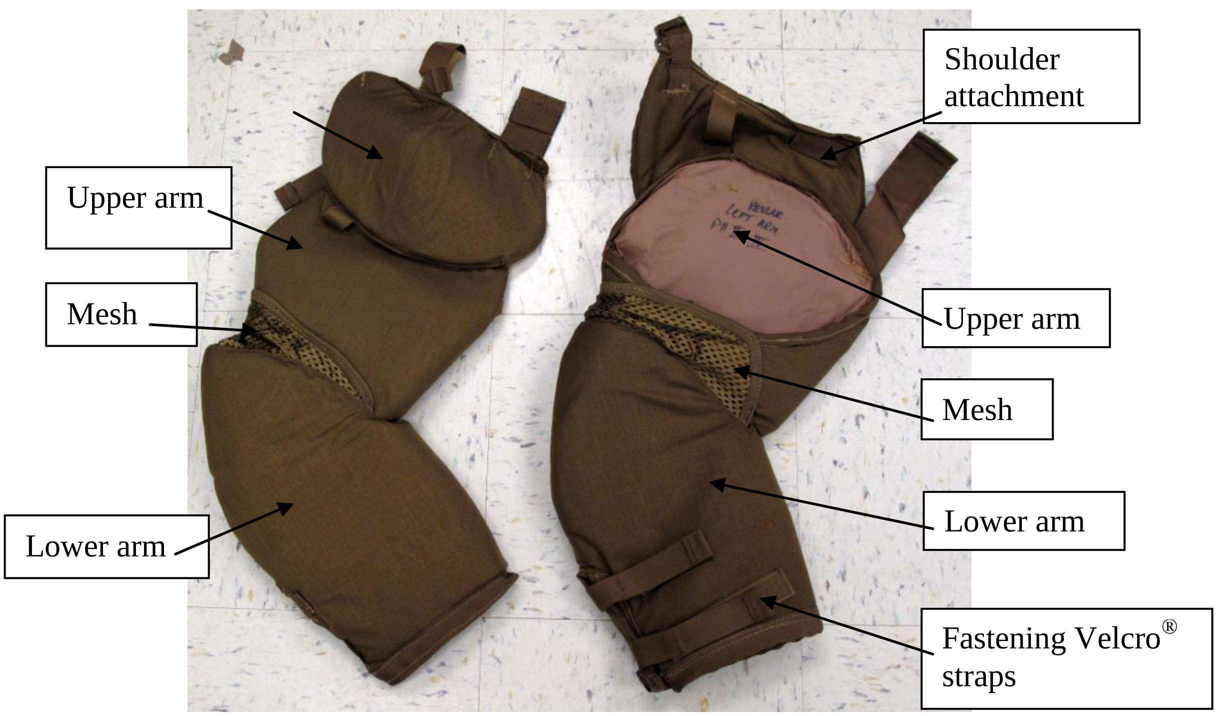


QG II Pant Front

QuadGard™ IV Armor System

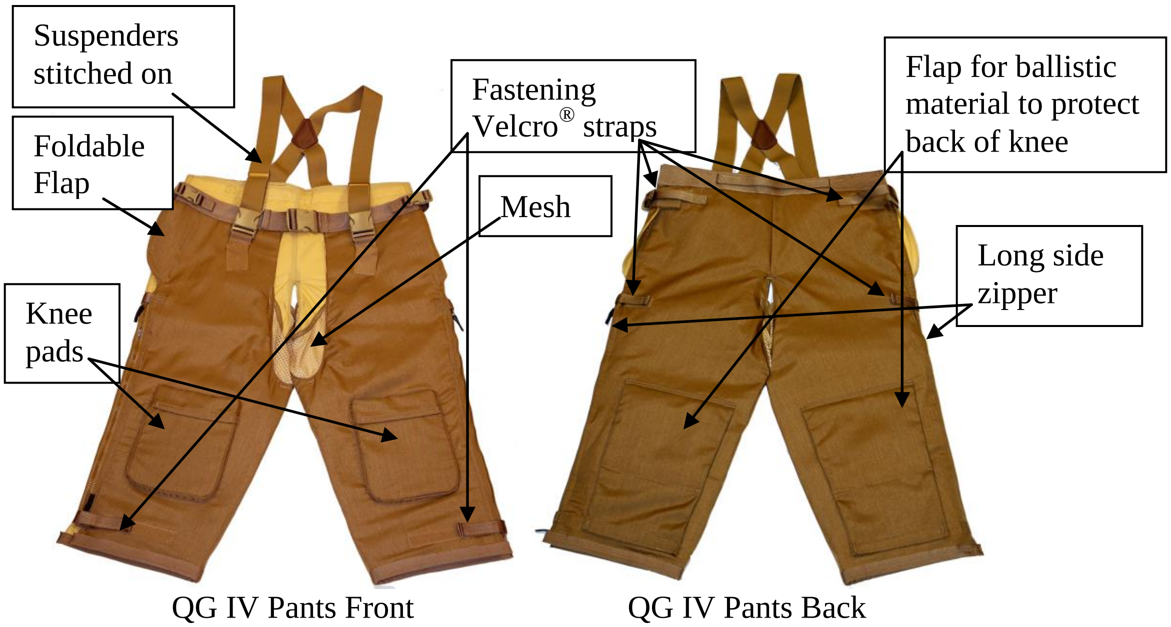
QuadGard™ IV is shown more explicitly in Figures 5 and 6. Just as seen in QuadGard™ II, QuadGard™ IV was formed with sewn-in ballistic material, but coverage was increased by enclosing more of the center back and outer leg. Knee pads were integrated into the leg units to eliminate the need for auxiliary knee pads. More robust suspenders were an important addition. QuadGard™ IV provides additional protection but at the cost of additional weight possibly additional heat stress. For this study, QuadGard™ IV ventilation was attained by opening the leg side flap located on the front thigh, whereas the condition of no ventilation was attained by closing the leg side flap. The three-piece arm unit remained the same as in QuadGard™ IV.

Figure 5. QuadGard™ IV Arm System



QG IV Arm Front QG IV Arm Back

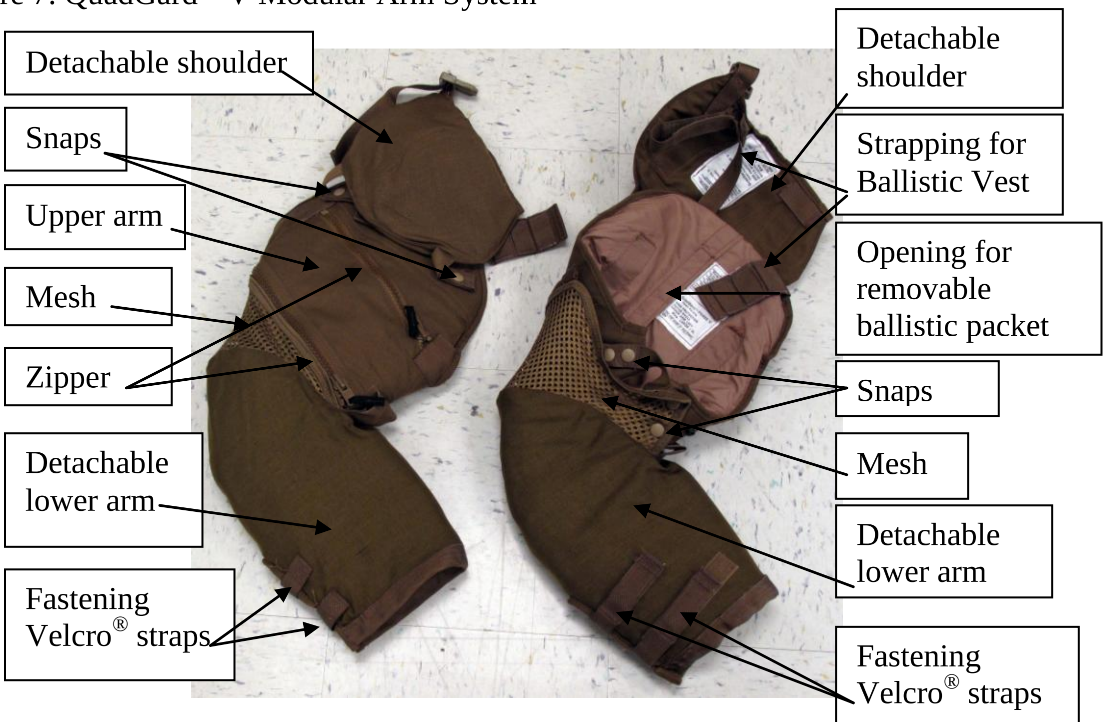
Figure 6. QuadGard™ IV Pant System



QuadGard™ V Armor System

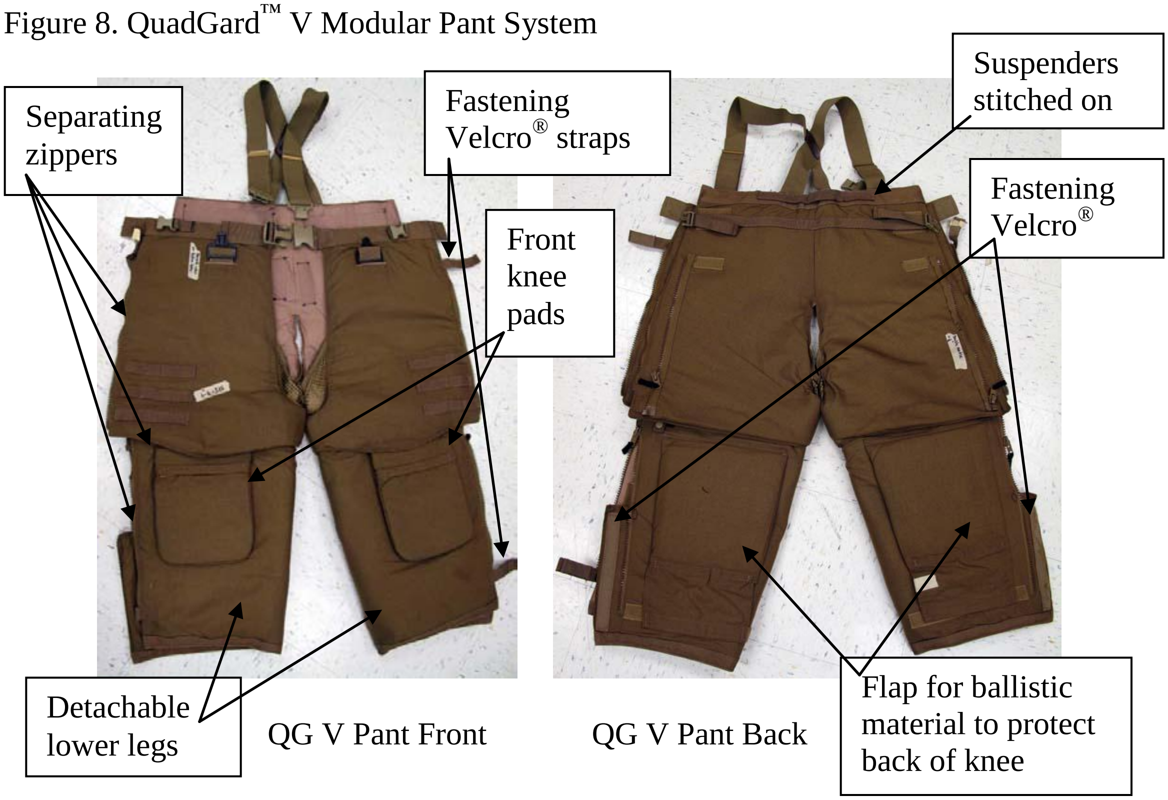
QuadGard™ V is more explicitly shown in Figures 7 and 8, as well as use of all or some components. Two major differences were incorporated into the QuadGard™ V Armor System. First, the ballistic material was encased in Rip-stop® and was removable for cleaning and/or insertion of a different ballistic pack. Second, the arm and leg units were modular and could be disassembled and varying components could be worn as the threat demanded. QuadGard™ V's three-piece arm units allowed for disassembly of the arm and shoulder units for partial protection of the arms and/or shoulder as needed for each mission. Snaps connected the shoulder piece to the upper arm section and a zipper plus snaps connected the lower arm to the upper arm for versatility and ease in donning and doffing. More robust suspenders, first used in QuadGard™ IV, continued to be an integral part of QuadGard™ V. Separating zippers connecting upper and lower leg sections provided adaptability and alternate levels of protection. Coverage was increased by enclosing more of the outer side leg, center back, and by covering previously exposed leg zippers.

Figure 7. QuadGard™ V Modular Arm System



QG V Arm Front QG V Arm Back

Figure 8. QuadGard™ V Modular Pant System



QG V Pant Front QG V Pant Back

Table 1 summarizes the fabrics used in all the QuadGard™ versions and provides the weight of the systems with the two different ballistic materials. QuadGard™ systems II and IV originally featured “sewn-in ballistic” packs. For this study the two existing systems were modified to allow for insertion of the two different ballistic materials, Kevlar® and Dyneema®. QuadGard™ II and IV were disassembled and the ballistic material was removed. They were reassembled without ballistic material to create test garments to allow insertion of ballistic material for each test. When they were reassembled, the ballistic material was inserted without being encased in Rip-stop® in order to duplicate the original designs.

Only QuadGard™ V had the ballistic material encased in Rip-stop®, which is the reason for conducting this 2-Phase study to permit two sets of comparisons (i.e. QuadGard™ II and IV, and QuadGard™ V configurations).

Table 1. QuadGard™ Design Features

	QuadGard™ II	QuadGard™ IV	QuadGard™ V
Carrier Shell	Cordura®	Cordura®	Cordura®
Ballistic Packs	Dyneema® OR Kevlar®	Dyneema® OR Kevlar®	Dyneema® OR Kevlar® (encased in Rip-stop® Nylon)
System Weight w/ Kevlar®	10.481 kg.	11.895 kg.	14.629 kg.
System Weight w/ Dyneema®	4.4575kg.	5.0775 kg.	6.838 kg.
Inner Shell Layer	Rip-stop® Nylon	Rip-stop® Nylon	Rip-stop® Nylon

Ballistic Material

Ballistic material was the second independent variable in this study with two levels: Kevlar® and Dyneema®. As discussed in Chapter II, Kevlar® is a trade name for a balanced plain weave fabric of aramid fibers, while Dyneema® is a trade name for a nonwoven fabric of unidirectional polyethylene (olefin) fibers. Within soft body armor, the number of layers depends on the desired level of protection and on the ballistic material used. Kevlar® was chosen due to its popularity and use by today's U. S. military and Dyneema® was chosen due to its functionality and ability to provide approximately the same level of protection as Kevlar® using fewer layers of fabric.

Fabric Weight (mass per unit area)

Fabric weight was measured according to the ASTM Standard Test Methods for Mass Per Unit Area of Fabric (ASTM D 3776-07) using a high precision scale (sensitive and capable of weighing within 0.1 % of the mass of the specimens being tested) to measure the fabric weight of five 100 cm^2 specimens to the nearest 0.001g for each fabric. Five samples from each fabric used in the armor systems were cut using a metric sample cutter manufactured by Industrial Laboratory Equipment Company (Model: ILE-CC-100). Weight was then reported in grams per meter squared (g/m^2).

Fabric Thickness

Fabric thickness was measured according to the ASTM Standard Test Method for Thickness of Textile materials (ASTM D 1777-96). Ten measurements to within 0.001" were taken using a thickness gauge manufactured by Industrial Laboratory Equipment Company, Inc. (Model: ILE-TG-2-D) at various locations along the length and width of the fabric. The pressure foot of the gauge was placed and allowed to stabilize on the fabric specimen for five seconds before each measurement was taken. Testing option 1 (at 0.6 psi pressure) was used to measure all sample fabrics, except for the lining fabric, which was measured using testing option 2. All ten measurements were averaged. Fabric characteristics of materials used in this study are presented in Table 2.

Table 2. QuadGard™ Fabric (Military Specified Fabrics) Characteristics

Fabric Name	Fiber Type	Fabric Structure	Yarns Per Inch (ypi)	Thickness (mm)** Avg.	std	Mass Per Unit Area* (gr/m^2) Avg.	std
Kevlar®***	Aramid	Balanced Plain Weave	30 x 30	0.34	0.01	233.16	1.76
Dyneema®	Olefin	2 Layer Non-woven Unidirectional		0.18	0.01	130.39	1.99
Cordura®	Nylon	Balanced Plain Weave	48 x 32	0.42	0.01	215.31	1.59
Rip-stop®	Nylon	Balanced Plain Weave (with slightly larger warps and filling yarns at regular intervals to create a grid within the fabric)	85 x 85	0.18	0.01	121.47	0.41
Mesh	Nylon	Warp Knit		0.64	0.01	178.55	0.59

*ASTM D 3776-07 Standard Test Methods for Mass Per Unit Area (weight) of Fabric

**ASTM D 1777-96 Standard Test Methods for Thickness of Textile Materials

***Style 705 Kevlar® KM-2, 54 inches wide with a denier of 750 to 850.

Dependent Variables

Dependent variables consisted of intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature, and moisture retention.

Intrinsic Clothing Insulation

Thermal insulation (R_t) was measured following ASTM method F 1291- 05 Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin. The data manipulated as given below to determine R_{cl}. Dry thermal resistance as measured by a sweating thermal manikin is the total thermal resistance of the clothing ensemble and surface air layer; whereas, intrinsic clothing insulation was calculated by subtracting the effect of the surface air layer from the dry thermal resistance.

Intrinsic Clothing Evaporative Resistance

Evaporative resistance (R_{et}) was measured following ASTM method F 2370 - 05 Standard Test Method for Measuring the Evaporative Resistance of Clothing using a Sweating Manikin. The data manipulated as given below to determine R_{ecl}. Evaporative resistance as measured by a sweating thermal manikin is the total evaporative resistance of the clothing ensemble and surface air layer; whereas, intrinsic evaporative resistance of the clothing ensemble was calculated by subtracting the effect of the surface air layer from the evaporative resistance. The dressed manikin's core temperature was brought to $37^{\circ}C \pm 0.2^{\circ}C$ and the system was allowed to reach steady-state (that is, the mean surface temperature of the manikin and the power input remained constant ± 3%).

Moisture Retention

Moisture retention was determined to be the difference between pre- and post-weight measurements. Each test armor system was inserted into large zip-lock bags and weighed after conditioning (i.e. placement of test garments in an environmental chamber set at 20°C ± 3°C with a relative humidity of 50% ± 3% for 24 hours prior to testing) and prior to dressing the manikin. Each test armor system was re-inserted into the same zip-lock bag and weighed immediately after completion of the test to ascertain the amount of moisture retained by each test armor system.

Micro-climate Temperature

Additional temperature sensors were strategically placed on the surface of the BDU to measure the temperature of the micro-environment between the BDU and the QuadGard™ to ascertain if the built-in ventilation feature altered micro-climate temperature.

Estimated Clothing Area Factor

The following calculations were found in the standard (ASTM, 2005).

$$f_{cl} = \frac{(1 + 1.97 \cdot R_t) + \sqrt{(1 + 1.97\, R_t)^2 - 4 \times 1.97\, R_a}}{2}$$

whereas, I_a = Average Nude R_t
= 0.0934

$R_{cl} = R_t - R_a/f_{cl}$

whereas, R_{cl} = intrinsic clothing insulation (EC·m^2/Watts),

R_t = total thermal resistance (insulation) of the clothing ensemble and surface air layer (°C·m^2/Watts),

R_a = thermal resistance of the air layer on the surface of the nude manikin (°C·m^2/Watts), = *nude R_{ct} value,*

f_{cl} = clothing area factor (dimensionless).

$R_{ecl} = R_{et} - R_{ea}/f_{cl}$

whereas, R_{ecl}= intrinsic evaporative resistance of the clothing ensemble (kPa·m^2/Watts),

R_{et} = total evaporative resistance of the clothing ensemble and surface air layer (kPa·m^2/Watts),

R_{ea} = evaporative resistance of the air layer on the surface of the nude manikin's sweating skin (kPa·m^2/Watts),

Skin Temperature	= 35°C,
Environmental Temperature	= 20°C,
Environmental Humidity	= 50%,
R_{ea}	= 0.0128 kPa·m^2/Watts);

f_{cl} = clothing area factor (dimensionless).

Equipment

Manikin Testing

Testing was conducted using a sweating thermal manikin, Walter – Perspiring Fabric Manikin Measurement System Version 3.0, housed in a state-of-the-art climate controlled chamber, manufactured by Conviron (Model: C1308), located in the Institute for Protective Apparel Research and Technology (IPART) laboratory at Oklahoma State University. The manikin was purchased from PolyU Technology and Consultancy Co. Ltd. (PTeC), where he was designed and built by Dr. Jintu Fan, Professor, Institute of Textiles & Clothing, The Hong Kong Polytechnic University, and his team of professionals. Figure 9 provides a visual view of Walter.

Figure 9. Walter - Perspiring Fabric Manikin Measurement System Version 3.0

Test Protocol

The environmental chamber, manufactured by Conviron (Model: C1308), that houses Walter was set at 20°C ± 3°C with a relative humidity of 50% ± 3%. The manikin's core temperature was maintained at 37°C ± 0.2°C. Air velocity satisfied the

ASTM F 2370 – 05 standard of being within ± 20 % of the mean value for data averaged over 5 minutes (see Appendix A). Testing was conducted using a modification of two ASTM Standard Test Methods, ASTM F 1291 – 05 and ASTM F 2370 – 05. ASTM F 2370 – 05 requires that a nude test be conducted in the same environmental conditions used for the clothing tests to measure the evaporative resistance (R_{ea}) provided by the air layer around the nude manikin by conducting a test in the same environmental conditions used for the clothing tests.

However, the Interceptor Vest with ballistic Kevlar is a thick garment; it required a long test period to reach saturation. Dr. Jintu Fan and John Wu of the Institute of Textiles & Clothing, The Hong Kong Polytechnic University, were consulted and as a result of this consultation, the protocol was modified in the following way. The BDU jacket, BDU pants, and Interceptor Vest was placed on Walter for a minimum of 48 hours to insure complete saturation of the standard garments. BDU and Interceptor data were treated as the nude data. This was the only modification made to the standard. The armor system to be tested was then placed on Walter.

In compliance with ASTM standards, the sweating thermal manikin was dressed in the conditioned standard garments which included: BDU jacket (standard issued), BDU pants (standard issued), Interceptor Vest (standard issued). Prior to testing, the standard garments plus test armor were placed in a controlled environment for approximately 24 hours prior to dressing the manikin.

Two additional temperature sensors, supplied by the manufacturer of Walter, were placed on the BDU pants above the thigh pocket flap to measure the micro-climate temperature between the BDU and the QuadGard™ Armor Systems to be tested. This placement was in close proximity to the built-in ventilation features of the QuadGard™ Armor Systems II and IV, and did not interfere with the placement of the manikin's fifteen (15) skin temperature sensors.

Study Design

Phase 1

A 2 x 3 design was used to compare two different ballistic materials, Kevlar® and Dyneema®, used in three (3) QuadGard™ variations, specifically: QG II, QG IV Ventilated, and QG IV Not-ventilated designed with sewn-in ballistic packets, but modified to allow for insertion of both ballistic materials. Ventilation on QG IV leg was accomplished through folding back and fastening the flap on the front thigh of the leg as shown in Figure 10.

Figure 10. QuadGard™ IV Ventilated

Phase 2

A 2 x 5 design was used to compare two different ballistic materials, Kevlar® and Dyneema®, used in five (5) QuadGard™ variations, specifically: QG V, QG V Arms, QG V Legs, QG V Upper arms, and QG V Upper legs.

Figure 11. Phase 2: QuadGard™ V Variations

Full Ensemble Arms Legs Upper Arms Upper Legs

Data Analysis

Statistical Analysis Software (SAS) version 9.1 was used to analyze the data. ANOVA was used to investigate QuadGard™ armor system and ballistic material differences in intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature, and moisture retention. Tukey Post Hoc procedures were used to determine statistically significant differences in the armor systems.

CHAPTER IV

MANUSCRIPT

Abstract

The purpose of this investigation was to examine the intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature, and moisture retention of three different QuadGard™ systems constructed with two ballistic materials. The study was broken into two Phases where each test was carried out in an environmental chamber set at a temperature of 20°C ± 3°C with a relative humidity of 50% ± 3%.

Test results from Phase 1 indicated that there was a significant ballistic material effect for intrinsic clothing insulation, $F(1,12) = 191.90$, $p < .0001$) and intrinsic clothing evaporative resistance, $F(1,12) = 104.59$, $p < .0001$). For micro-climate temperature there was a significant two-way armor system-by-ballistic material interaction and the simple effects were significant for ballistic material, $F(1,12) = 9.34$, $p = .01$). Since the moisture retention data did not satisfy the assumption of homogeneity of variance, a logarithmic transformation was performed on the data. Analysis of the log transformed data showed a significant ballistic material effect for moisture retention, $F(1,12) = 19.31$, $p = .0009$). Phase 2 results indicated that there was a significant ballistic material effect for intrinsic

clothing insulation, $F(1,20) = 51.08$, $p < .0001$) and intrinsic clothing evaporation, $F(1,20) = 31.72$, $p < .0001$).

Test results from Phase 1 indicated a significant armor system effect for intrinsic clothing insulation, $F(2,12) = 5.71$, $p = .0181$). For micro-climate temperature there was a significant two-way armor system-by-ballistic material interaction and the simple effects were significant for armor system, $F(2,12) = 30.30$, $p < .0001$). Test results from Phase 2 indicated that there was a significant armor system effect for three dependent variables: 1) intrinsic clothing insulation, $F(4,20) = 320.22$, $p < .0001$); 2) intrinsic clothing evaporative resistance (R_{ecl}), $F(4,20) = 293.63$, $p < .0001$); and 3) micro-climate temperature, $F(4,20) = 83.98$, $p < .0001$). As in Phase 1, the moisture retention data did not satisfy the assumption of homogeneity of variance, a logarithmic transformation was performed on the data. Analysis of the log transformed data showed a significant armor system effect for moisture retention, $F(4,20) = 107.37$, $p < .0001$).

The findings indicated that fabric and garment design influence the thermal burden of the garment ensemble. The findings give merit to and show the benefit of modularity, especially for military personnel who will be in or driving an armored vehicle.

Introduction

Total heat transmitted through clothing, the sum of the dry heat transfer and the evaporative heat transfer, is an important dimension of the effectiveness of functional clothing design and the suitability of clothing systems for intended end uses (Fan, Chen, & Zhang, 2005). A goal of clothing is to maintain the human body's thermal equilibrium and to protect the body against a variety of environments (Yun, Xi-ying, Er-li, Xiao-hong, & Jian-Yong, 2006; Woodcock, 1962; Zhang, Gong, Yanai, & Tokura, 2002). Even with improvements in ballistic protective clothing systems provided by new performance fibers and design advancements, there is still a propensity towards retention of dry thermal heat and reduction of moisture transfer to the environment.

While protecting the soldier from projectiles fired from handguns and flying shrapnel from explosives is paramount, it is equally important to provide protective clothing that does not hamper the thermoregulation mechanism of the human body or reduce the ability of the soldier to move at will. Therefore, the design of ballistic protective armor is a compromise between multiple competing priorities including protection from ballistic and blast threats, thermal comfort, mobility and weight.

Researchers agree that protective clothing systems play a role in the development of heat stress when worn by subjects in environments that are hot, humid, or both, as well as when the subject is involved in vigorous physical activity (McCullough, 2005a). The degree to which body armor affects the heat exchange between the soldier and the environment is an important factor that should be considered when evaluating the effectiveness of ballistic protective clothing systems.

Purpose

The purpose of this study was to investigate the effects of fabrication and design features on intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature, and moisture retention of two different ballistic materials and three different QuadGard™ systems: QG II, QG IV, and QG V. The QuadGard™ system was designed to provide small arms and fragmentation protection for the soldiers' arms and legs. Specifically, the objectives of this study were to determine the differences between: 1) eight armor systems' dry thermal and evaporative resistance as measured by a sweating manikin, 2) two types of ballistic materials on dry thermal and evaporative resistance as measured by a sweating manikin for the previously mentioned armor systems, 3) the micro-climate temperature measured between the battle dress uniform (BDU) and the QuadGard™ pant systems as measured by temperature sensors located on the sweating manikin's front thigh, and 4) eight armor systems' moisture retention as measured through pre- and post-test weights.

QuadGard™ Development

QuadGard™ limb armor systems were developed by Dr. Donna Branson and her team at Oklahoma State University in partnership with FSTechnology LLC, the Naval Research Laboratory, and the Army Research Laboratory (Peksoz, Branson, & Farr, 2007; Matic, Hubler, Sprague, Simmonds, Rupert, Bruno, Frost, Branson, Farr, & Peksoz, 2006). Multiple prototypes of QuadGard™ were developed and each subsequent version of QuadGard™ increased the coverage provided to the soldier and added new design features.

Independent Variables

There are two independent variables in this study, ballistic material and armor system. The independent variable "ballistic material" has two levels, Dyneema® and Kevlar®. The research was conducted in two phases due to major design differences between QG V and the other two armor systems. The ballistic material in QG II and QG

IV was not encased in Nylon Rip-stop® as QG V was. Thus, an additional two layers of lining material was present in QG V that was not present in QG II and IV.

In Phase 1, independent variable “armor system” had three levels: QG II, QG IV Not Ventilated, and QG IV Ventilated. Ventilation of QG IV Ventilated was accomplished by folding open the upper flap located on the outer side of each front thigh piece of QuadGard™ IV. In Phase 2, independent variable “armor system” had five levels: QG V, QG V Arms, QG V Legs, QG V Upper Arms, and QG V Upper Legs. Figure 12 presents the three different armor systems, QuadGard™ II, IV and V complete, the focus of interest in this study. QuadGard™ V is a modular design and the arm and leg units can be disassembled to permit wearing only components necessary for a specific mission.

Figure 12. QuadGard™ Armor Systems While Being Tested on Walter

QuadGard™ II QuadGard™ IV QuadGard™ V

Dependent Variables

A sweating manikin housed in an environmental chamber measured total R_t and total R_{et}. The dependent variables intrinsic clothing insulation (R_{cl}) and intrinsic clothing (R_{ecl}) evaporative resistance were calculated from the total dry thermal resistance and the total evaporative resistance measured by the manikin, by subtracting the effect of the surface air layer. Micro-climate temperature was measured by the thermal manikin; while, moisture retention was determined through pre- and post- test weights.

Methods and Procedures

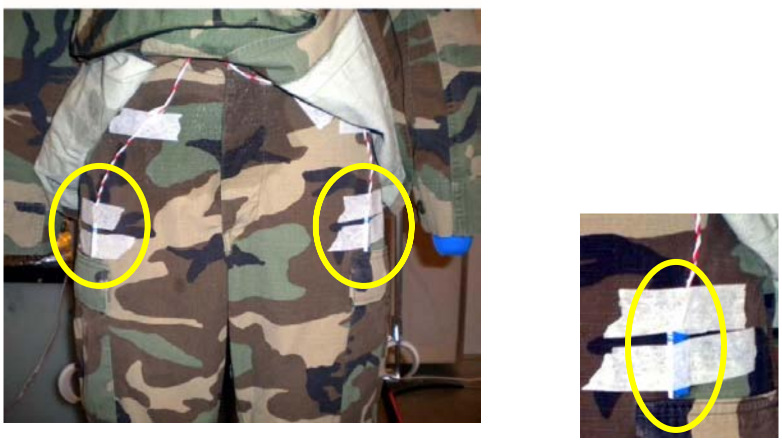
The three QuadGard™ prototypes included in this study were: QG II, which featured the least amount of coverage; QG IV, which covered a larger amount of body surface than QG II; and QG V, which covered a larger amount of body surface than QG IV. In addition, QG V was designed to be modular, which permitted disassembly to allow varying components to be worn as the threat demanded. QuadGard™ II and IV were designed to feature sewn-in ballistic panels, while QuadGard™ V was designed to feature insertable packets of ballistic material covered in Rip-stop® (a durable plain weave, nylon fabric). For this study, QG II and IV were modified to allow for the insertion and removal of the two different test ballistic materials, which were not covered in Rip-stop®. The layers of ballistic material were stitched together to make them insertable to simulate the original design. Due to the above mentioned differences in the QuadGard™ systems, a 2-phase study was undertaken.

Test Protocol

Walter, a novel sweating thermal manikin, located at the Institute for Protective Apparel Research and Technology (IPART) of Oklahoma State University was used in this study. Walter was housed in an environmental chamber, held in a static position, and a core temperature was maintained of $37^{\circ}C \pm 0.2^{\circ}C$. The testing environment included temperature set at $20^{\circ}C \pm 3^{\circ}C$ with a relative humidity of 50% ± 3%. Air velocity satisfied the ASTM F 2370 – 05 standard of being within ± 20 % of the mean value for data averaged over 5 minutes. In accordance with ASTM standards, all garments were conditioned in a controlled environment, set at $20^{\circ}C \pm 3^{\circ}C$ with a relative humidity of 50% ± 3%, prior to dressing the sweating manikin.

Prior to testing, each pre-conditioned garment was placed in a specified, non-permeable plastic bag and weighed. This step was completed for all garments placed on the manikin, including the standard ensemble. The manikin was first dressed in the standard issued BDU jacket, BDU pants, and Interceptor vest. In order to reach full saturation and to be held constant throughout the remaining tests, the standard ensemble was placed on Walter for a minimum of 48 hours prior to placement of each QuadGard™ armor system to be tested. The QuadGard™ armor to be tested was then positioned on a fully functioning thermal manikin, i.e., QG armor was placed over the saturated standard ensemble. Two additional temperature sensors were positioned over the front thigh pocket of the BDU pant to measure micro-climate temperature and tested for a minimum of eight hours once steady state was reached. Figure 13 illustrates the placement of micro-climate temperature sensors on the BDU pant. The thermal manikin's computer software recorded measurement of temperatures and heat supply every 30 seconds. At the completion of each test, the tested QuadGard™ system was once again placed in the same plastic bag and re-weighed to record weight gain due to moisture retention. Each test was replicated three times.

Figure 13. Placement of Microclimate Temperature Sensors on the BDU Pant



The standards require that a nude test be conducted in the same environmental conditions used for the clothing tests. Since the Interceptor vest is a thick garment and is an important piece of the three basic garments used as the *nude test*, a longer testing period was required to reach saturation. Prior to dressing the manikin, the manikin was operated for a full 24 hours as directed by the standards (ASTM, 2005). Once the manikin had operated a full 24 hours, the manikin was dressed for the nude test, as discussed earlier, and operated for a full 48 hours, an allotment of time determined by the measurement of R_t and R_{et} for full saturation of the basic garments, including the Interceptor vest. Once saturation was met, testing on QuadGard™ systems began. Each QuadGard™ system or configuration of QuadGard™ system was tested for a minimum of seven hours. Following the removal of one armor system, the next armor system and subsequent armor systems to be tested were immediately placed on the manikin, one right after the other. Testing continued in this fashion until the manikin had operated for a period of seven days. To prevent mold and mildew contamination after a full week of testing, the BDU pant, the BDU jacket, and the Interceptor vest were weighed separately in their own plastic bag, Walter was shut down, and the BDU was laundered. All ballistic inserts were removed from the Interceptor vest and all of the separated pieces were placed in a controlled environment set at $20^{\circ}C \pm 3^{\circ}C$ with a relative humidity of $50\% \pm 3\%$ to dry and be re-conditioned for a minimum of 48 hours.

Results and Discussion

Material and armor treatments used in both phases of this research were measured for intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature, and moisture retention. Analysis of variance was used to determine if there were significant differences by armor system, ballistic material, and armor system-by-ballistic material interaction. An alpha level of .05 for all statistical tests was used. Hartley's F_{max} test was used to check for homogeneity of variance. Intrinsic clothing insulation and micro-climate temperature passed this test at the .25 level, while intrinsic clothing evaporative resistance passed this test at the .05 level. The assumption of homogeneity of variance was accepted for these three dependent variables. However, moisture retention failed this test indicating heterogeneous variances in both Phases 1 and 2. When heterogeneous variances are found, the recommended procedure is the transformation of the dependent variable to try and achieve homogeneity (Freund & Wilson, 2003; Beckman & Tietjen, 1973). A number of different transformations in the

Box and Cox (1964) family were tried and a logarithmic transformation seemed to be the best, although not totally satisfactory for moisture retention. For moisture retention, the analysis using the logarithmic transformation is presented.

Phase 1

Two ballistic material treatments, Dyneema® and Kevlar®, were evaluated in Phase 1. The three armor systems evaluated in Phase 1 were QG II, QG IV Ventilated, and QG IV Not ventilated.

Moisture Retention

In their 2008 study on a sweating, thermal manikin, Celcar, Meinander, & Gersak weighed each garment piece before and after each test to determine the amount of moisture retained in the garment ensemble, which evaporated throughout the clothing and condensed in each article of clothing. This method was used in this study to determine the amount of moisture retention in QuadGard™ body armors.

Moisture retention failed the Hartley's F_{max} test indicating heterogeneity of variance. When heterogeneous variances are found, the recommended procedure is the transformation of the dependent variable to try and achieve homogeneity (Freund & Wilson, 2003; Beckman & Tietjen, 1973). A number of different transformations in the Box and Cox (1964) family were tried and a logarithmic transformation seemed to be the best, although not totally satisfactory for moisture retention. For moisture retention, the analysis using the logarithmic transformation is presented.

A factorial design ANOVA revealed that there was no significant two-way armor system-by-ballistic material interaction for moisture retention, $F(2,12) = 0.42$, $p = .6672$, as shown in Table 3. A significant ballistic material effect $F(1,12) = 19.31$, $p = .0009$), was found as shown in Table 3. Therefore, the null hypothesis stating that there was no significant difference for moisture retention between the ballistic material, Kevlar® and Dyneema®, was rejected. The mean moisture retention for ballistic material, Kevlar®, consistently measured less than for the ballistic material, Dyneema®, regardless of design as shown in Table 4. One possible reason for this phenomenon could be due to the different fabric structures of the ballistic materials, Kevlar® and Dyneema®. Kevlar® is a balanced plain weave, while Dyneema® is unidirectional, non-woven fabric. Although, it would seem that the open spaces created from the interlacing of the aramid fibers in the balanced, plain weave found in Kevlar® would provide more space for moisture to collect and result in higher moisture retention, instead Dyneema® retained more moisture. It could be possible that the openness of the Kevlar® weave could also have provided more area through which the moisture could evaporate, resulting in lower moisture retention. On the other hand, the unidirectional layers that form Dyneema® have the potential for more condensation to form between the layers, which could account for the higher moisture retention.

Table 3. Phase 1: ANOVA of Moisture Retention Using a Logarithmic Transformation

Source	df	Sum of Squares	Mean Square	F	Sig.
Ballistic Material	1	0.44074899	0.44074899	19.31	**0.0009**
Armor System (QG)	2	0.0223534	0.0011177	0.05	0.9524
QG * Ballistic Material	2	0.0191099	0.0095550	0.42	0.6672
Error	12	0.2738574	0.0228215		
Corrected Total	17	0.7359516			

Table 4. Phase 1: Moisture Retention Means

	QG II		QG IV Not Ventilated		QG IV Ventilated	
kg	Kevlar	Dyneema	Kevlar	Dyneema	Kevlar	Dyneema
Mean	0.136	0.201	0.145	0.193	0.150	0.191
SD	0.033	0.023	0.002	0.026	0.034	0.011

Results of analysis of variance for moisture retention indicated that there was no significant armor system effect, $F(2,12) = 0.05$, $p = .9524$, as shown in Table 3. Therefore, the null hypothesis stating that there was no significant difference for moisture retention between the QuadGard™ systems II, IV Not Ventilated, and IV Ventilated was not rejected.

Intrinsic Clothing Insulation

A factorial ANOVA was performed to find out if there were significant differences by treatment for intrinsic clothing insulation. There was no significant two-way armor system-by-ballistic material interaction for intrinsic clothing insulation, $F(1,12) = 2.97$, $p = .0898$, as shown in Table 5. Results of analysis of variance for intrinsic clothing insulation indicated a significant ballistic material effect, $F(1,12) = 191.90$, $p < .0001$. Therefore, the null hypothesis stating that there was no significant difference for intrinsic clothing insulation between the ballistic materials Kevlar® and Dyneema® was rejected.

Table 5. Phase 1: ANOVA Intrinsic Clothing Insulation

Source	df	Sum of Squares	Mean Square	F	Sig.
Ballistic Material	1	0.02226	0.02226	191.9	**<.0001**
Armor System (QG)	2	0.00133	0.00066	5.71	**0.0181**
QG * Ballistic Material	2	0.00069	0.00034	2.97	0.0898
Error	12	0.00139	0.00012		
Corrected Total	17	0.02567			

It is interesting to note that the mean intrinsic clothing insulation for ballistic material, Dyneema®, consistently measured less than the ballistic material, Kevlar®, regardless of design as seen in Table 6. The means for Dyneema® ranged between .0483 and .0617, while the means for Kevlar® ranged between .1057 and .1387. For the same level of protection, fewer layers of Dyneema® were used than Kevlar® in the ballistic pack. Kamenidis found that Dyneema® had lower thermal resistance (R_{ct}) than Kevlar® for the same level of protection while testing textile packs on a sweating guarded hotplate (2009). These findings using a sweating guarded hotplate on layers of ballistic material are consistent with the findings from this study on armor systems using a thermal manikin. For the R_{ct} testing on the fabric packs, the packs were not saturated with water, while the manikin testing on the armor systems were saturated with water. In their 2003 study, Chen, Fan, & Zhang state that perspiration reduces clothing thermal insulation. In this study, Dyneema® consistently measured higher than Kevlar® for moisture retention, which may have played a role in Dyneema's lower thermal insulation as compared to Kevlar® in moisture retention. In other words, Dyneema's lower thermal resistance (R_{ct}) and higher moisture retention are the possible reasons that QG armor systems made from Dyneema® have lower intrinsic clothing insulation than those made from Kevlar®.

Table 6. Phase 1: Intrinsic Clothing Insulation Means

R_{cl}		QG II		QG IV Not Ventilated		QG IV Ventilated	
(˚C m^2/W)		Kevlar	Dyneema	Kevlar	Dyneema	Kevlar	Dyneema
	Mean	0.1057	0.0527	0.1387	0.0617	0.1293	0.0483
	SD	0.0065	0.0101	0.0150	0.0032	0.0047	0.0171

Results of analysis of variance for intrinsic clothing insulation indicated a significant armor system effect, $F(2,12) = 5.71$, $p = .0181$ (Table 5). Therefore, the null hypothesis stating that there was no significant difference for intrinsic clothing insulation between the QuadGard™ systems II, IV Not Ventilated, and IV Ventilated, was rejected.

Post Hoc Tukey Multiple Comparison analysis revealed that there was a significant difference between QG IV Not Ventilated and QG II for intrinsic clothing insulation, as seen in Figure 14. However, there was no significant difference between QG II and QG IV Ventilated for intrinsic clothing insulation, nor was there a significant difference between QG IV Ventilated and QG IV Not Ventilated.

Figure 14. Significant Differences for Intrinsic Clothing Insulation among Phase 1 Armor Systems Based on Post Hoc $Tukey_{0.05}$ Analysis

QG IV Not Ventilated	QG IV Ventilated	QG II
0.1002a	0.0888ab	
		0.0792b

As discussed earlier, QG IV was designed to provide more coverage than QG II. It is a positive finding to learn that use of the ventilation feature of QG IV appears to have resulted in no significant difference in intrinsic clothing insulation as compared to the intrinsic clothing insulation of QG II, an armor system with less coverage of the body. R_{cl} reflects the heat transfer through conduction, convection, and radiation (Holmer, Nilsson, Havenith, & Parsons, 1999; Chen, et al., 2003). QG II covers a smaller area of the body and therefore, has lower intrinsic clothing insulation due to more heat loss through conduction. As there was some air movement in the environmental chamber, the ventilation feature in QG IV helped reduce intrinsic clothing insulation probably due to more heat loss through convection.

Intrinsic Clothing Evaporative Resistance

A factorial design ANOVA was performed to find out if there were significant differences by treatment for intrinsic clothing evaporative resistance. There was no significant two-way armor system-by-ballistic material interaction for intrinsic clothing evaporative resistance $F(2,12) = 0.1667$, $p = 0.1667$), as shown in Table 7.

Table 7. Phase 1: ANOVA Intrinsic Clothing Evaporative Resistance

Source	df	Sum of Squares	Mean Square	F	Sig.
Ballistic Material	1	638.4117336	638.4117336	104.59	**<.0001**
Armor System (QG)	2	10.0968048	5.0484024	0.83	0.4608
QG * Ballistic Material	2	25.4897134	12.7448567	2.09	0.1667
Error	12	73.2471293	6.1039274		
Corrected Total	17	747.2453811			

Results of analysis of variance for intrinsic clothing evaporative resistance indicated a significant ballistic material effect, $F(1,12) = 104.587$, $p < 0.0001$. Therefore, the null hypothesis stating that there was no significant difference for intrinsic clothing evaporative resistance between the ballistic material Kevlar® and Dyneema® was rejected. It is interesting to note that Dyneema®, consistently measured lower in intrinsic clothing evaporative resistance than the ballistic material, Kevlar®, in all armor systems tested in Phase 1, as shown in Table 8. Kamenidis found that one layer of Kevlar® fabric had a lower evaporative resistance (R_{et}) than one layer of Dyneema® fabric (2009). However, for multilayer Kevlar® and Dyneema® with a similar level of protection, the evaporative resistance data were "out of testing range" (>999) of the sweating guarded hotplate (Kamenidis, 2009). However, a sweating, thermal manikin was capable of obtaining intrinsic clothing evaporative resistance data for armor systems made from multi-layer ballistic material, since unlike the hotplate test, the ballistic material did not cover all of the manikin's skin. There was more space between the manikin skin and the clothing and there were more openings due to garment design, such as sleeve and neck openings. This may be the reason that the manikin intrinsic clothing evaporative resistance was not "out of testing range". Since one layer of Kevlar® fabric has lower evaporative resistance than one layer of Dyneema® fabric, a possible explanation for Dyneema® consistently measuring lower in intrinsic clothing evaporative resistance than the ballistic material, Kevlar® is that there are fewer layers of Dyneema® than Kevlar® for the same level of protection. In addition, intrinsic clothing evaporative resistance is related to evaporative heat loss, which could indicate that QG armor systems made from Dyneema® have more evaporative heat loss and therefore, maybe more comfortable than those made from Kevlar®.

There was no significant armor system effect for intrinsic clothing evaporative resistance between QuadGard™ II, IV Not ventilated, and IV Ventilated, $F(2,12) = 0.83$, $p = 0.4608$), as shown in Table 7. Therefore, the null hypothesis stating that there was no significant difference for intrinsic clothing evaporative resistance between the QuadGard™ systems II, IV Not Ventilated, and IV Ventilated was not rejected.

Table 8. Phase 1: Intrinsic Clothing Evaporative Resistance Means

R_{ecl}		QG II		QG IV Not Ventilated		QG IV Ventilated	
(Pa m^2/W)		Kevlar	Dyneema	Kevlar	Dyneema	Kevlar	Dyneema
	Mean	28.363	16.241	28.408	19.511	29.807	15.093
	SD	0.904	3.375	0.533	1.007	4.795	0.364

Micro-climate Temperature

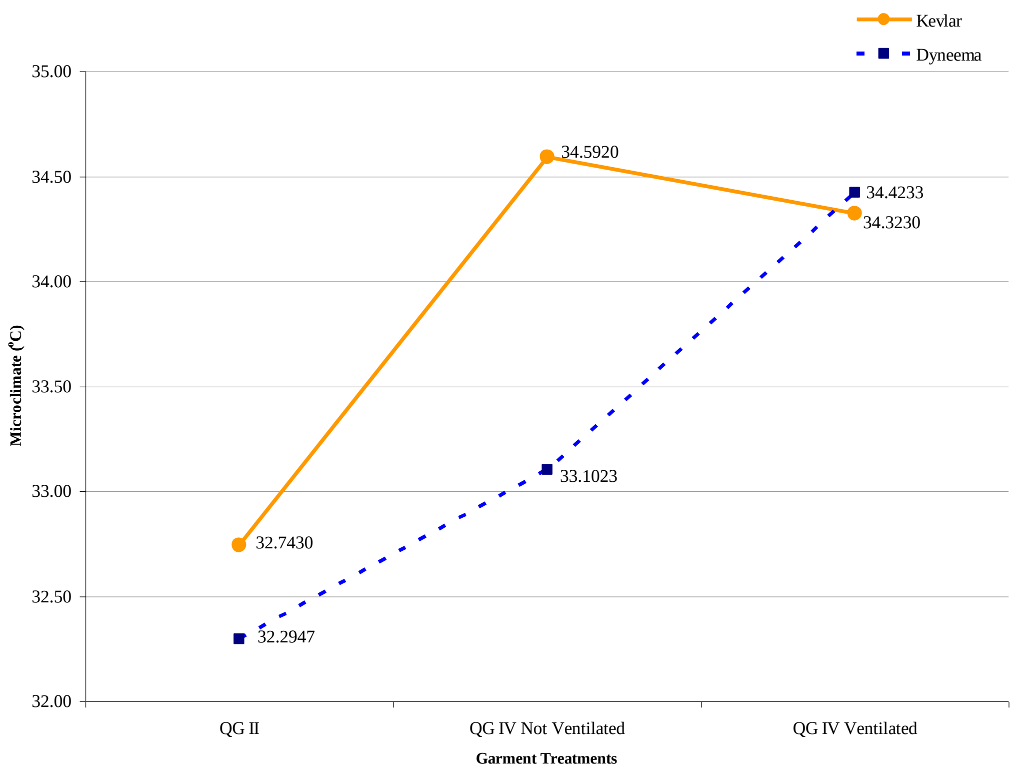
A factorial design ANOVA was performed to find out if there were significant differences by treatment levels for micro-climate temperature, as shown in Table 9.

Table 9. Phase 1: ANOVA Micro-climate Temperature

Source	df	Sum of Squares	Mean Square	F	Sig.
Ballistic Material	1	1.6885094	1.6885094	9.34	**0.0100**
Armor System (QG)	2	10.9593951	5.4796976	30.3	**<.0001**
QG * Ballistic Material	2	1.9567551	0.9783378	5.41	**0.0211**
Error	12	2.1699480	0.1808290		
Corrected Total	17	16.7746076			

Analysis of variance indicated that there was a significant two-way armor system-by-ballistic material interaction for micro-climate temperature, $F(2,12) = 5.41$, $p = 0.0211$, see Table 9. Figure 15 presents a graph of the two-way armor system-by-ballistic material interaction for micro-climate temperature, showing a different pattern by ballistic material.

Figure 15. Phase 1: QuadGard™ Systems-by-Ballistic Material Interaction Plot for Micro-climate Temperature



Since there was an interaction, the main effect cannot be interpreted, but it is appropriate to look at the simple effects (Freund & Wilson, 2003). As a result, three t-tests were completed, along with two $\text{Tukey}_{0.05}$ Post Hoc Analyses. For QG II, there was no significant difference between Kevlar® and Dyneema® $F(1,12) = 1.6499$, $p = .223$ and for QG IV Ventilated there was no significant difference between Kevlar® and Dyneema® $F(1,12) = .002$, $p = .963$). However, for QG IV Not Ventilated there was a significant difference between Kevlar® and Dyneema® with Dyneema® measuring lower $F(1,12) = 18.407$, $p = .001$). Table 10 presents the means and standard deviations.

Table 10. Phase 1: Micro-climate Temperature Means

	QG II		QG IV Not Ventilated		QG IV Ventilated	
°C	Kevlar	Dyneema	Kevlar	Dyneema	Kevlar	Dyneema
Mean	32.743	32.295	34.592	33.102	34.323	34.423
SD	0.411	0.178	0.533	0.251	0.698	0.224

The Tukey Post Hoc analyses results for micro-climate temperature for Phase 1 among the armor systems are presented in Figures 16 and 17. Tukey revealed that QG II in Kevlar® was significantly different than both QG IV Ventilated and QG IV Not Ventilated, which were not significantly different from each other. Tukey also revealed that QG IV Not Ventilated in Dyneema® was significantly different than both QG II and QG IV Ventilated, which were not significantly different from each other. It is interesting to note that the lowest micro-climate temperature measurement was under QG II, the armor system with the least amount of surface coverage. QG II also had the smallest intrinsic clothing insulation. The fact that QG II covered the least amount of surface area could account for QG II having the lowest intrinsic clothing insulation and micro-climate temperature.

Figure 16. Significant Differences for Micro-climate Temperature among Phase 1 Armor Systems in Kevlar® Based on Post Hoc $Tukey_{0.05}$ Analysis

QG IV Not Ventilated	QG IV Ventilated	QG II
34.592a	34.323a	
		32.743b

Figure 17. Significant Differences for Micro-climate Temperature among Phase 1 Armor Systems in Dyneema® Based on Post Hoc Tukey$_{0.05}$ Analysis

QG IV Ventilated	QG IV Not Ventilated	QG II
34.423a		
	33.102b	32.295b

A summary of the statistical analyses of Phase 1 can be seen in Table 11.

Table 11. Phase 1: Summary of Statistical Results

	Ballistic Material			Armor System	
	Significant Difference	Explanation	Significant Interaction	Significant Difference	Explanation
R_{cl}	Yes	Dyneema® < Kevlar®	No	Yes	2 groups: 1st group being: QG IV Not Ventilated and QG IV Ventilated 2nd group being: QG IV Ventilated and QG II
R_{ecl}	Yes	Dyneema® < Kevlar®	No	No	
Micro-climate Temperature	Simple Effects, Yes	Dyneema® < Kevlar® For Only QG II & QG IV Not Ventilated	Yes	Simple Effects, Yes	Kevlar®, QG II < QG IV Ventilated and QG IV Not Ventilated Dyneema® , QG II and QG IV Not Ventilated < QG IV Ventilated
Moisture Retention	Log transformed data; Yes	Dyneema® < Kevlar®	No	Log transformed data; No	

Phase 2

Two ballistic material treatments, Dyneema® and Kevlar®, were evaluated in Phase 2. As discussed previously, five (5) different variations of the modular QuadGard™ V, were evaluated in Phase 2 included QuadGard™ V Complete (i.e. arms and legs), QuadGard™ V Arms, QuadGard™ V Legs, QuadGard™ Upper Arms, and QuadGard™ V Upper Legs.

Moisture Retention

Moisture retention failed the Hartley's F_{max} test indicating heterogeneity of variance. When heterogeneous variances are found, the recommended procedure is the transformation of the dependent variable to try and achieve homogeneity (Freund & Wilson, 2003; Beckman & Tietjen, 1973). A number of different transformations in the Box and Cox (1964) family were tried and a logarithmic transformation seemed to be the best, although not totally satisfactory for moisture retention. For moisture retention, the analysis using the logarithmic transformation is presented.

A factorial design ANOVA was performed to find out if there were significant differences in treatment levels for moisture retention. There was no significant two-way armor system-by-ballistic material interaction for moisture retention, $F(4,20) = 1.42$, $p = 0.2650$, as shown in Table 12.

There was no significant ballistic material effect for moisture retention, $F(1,20) = 1.22$, $p = .2832$. Therefore, the null hypothesis that stated there was no significant difference between the ballistic materials, Kevlar® and Dyneema®, was not rejected.

Results of analysis of variance for moisture retention indicated a significant armor system effect, F(4,20) = 107.37, p <.0001. Therefore, the null hypothesis that stated there was no significant difference between armor system treatments was rejected. Table 13 presents the moisture retention means of all of the QuadGard™ V versions for both ballistic materials.

Table 12. Phase 2: ANOVA of Moisture Retention Using a Logarithmic Transformation

Source	df	Sum of Squares	Mean Square	F	Sig.
Ballistic Material	1	0.07553712	0.07553712	1.22	0.2832
Armor System (QG)	4	26.6788796	6.6697199	107.37	**<.0001**
QG * Ballistic Material	4	0.3517794	0.0879449	1.42	0.265
Error	20	1.2423945	0.0621197		
Corrected Total	29	28.3485906			

Table 13. Phase 2: Moisture Retention Means

	QG V		QG V Arms		QG V Legs		QG V Upper Arms		QG V Upper Legs	
kg	K	D	K	D	K	D	K	D	K	D
Mean	0.2380	0.1877	0.0483	0.0487	0.1992	0.1823	0.0213	0.0135	0.0978	0.1270
SD	0.0360	0.0149	0.0045	0.0076	0.0766	0.0870	0.0089	0.0005	0.0042	0.0325

Figure 18 presents the Post Hoc Tukey Comparison Analysis with QuadGard™ V versions listed from highest to lowest log mean moisture retention (left to right). According to the Tukey Post Hoc results on the transformed data, four groups were formed. QG V and QG V Legs had the highest mean amount of moisture retention and were significantly different from each other. QG V and QG V Legs differed significantly from all other QG V configurations. QG V Upper Legs retained the third highest mean moisture retention, followed by QG V Arms, which were not significantly different from each other. QG V Arms retained the second lowest mean moisture, followed by QG V Upper Arms, which were significantly different from each other. It is logical and interesting to note that the largest configurations of QG V that cover the largest surface area of the body retained the highest levels of moisture.

Figure 18. Significant Differences for Moisture Retention Using a Logarithmic Transformation among Phase 2 Armor Systems Based on the Post Hoc Tukey$_{0.05}$ Analysis

QG V	QG V Legs	QG V Upper Legs	QG V Arms	QG V Upper Arms
-1.5590a	-1.7150a			
		-2.2045b		
			-3.0317c	
				-4.1055d

Intrinsic Clothing Insulation

A factorial ANOVA was performed to find out if there were significant differences by treatment for intrinsic clothing insulation. There was no significant two-way armor system-by-ballistic material interaction for intrinsic clothing insulation, as given in Table 14. Results of analysis of variance for intrinsic clothing insulation indicated a significant ballistic material effect $F(1,20) = 51.08$, $p < .0001$). The results in Phase 2 were similar to Phase 1 in that the ballistic material, Dyneema®, consistently measured lower in intrinsic clothing insulation than the ballistic material, Kevlar®, as shown in Table 15. It is worth noting once again that in an earlier study, Dyneema® had lower thermal resistance than Kevlar® for the same level of protection while testing textile packs on a sweating guarded hotplate (Kamenidis, 2009). The findings from this study, in both Phases are consistent with the results in the Kamenidis study (2009).

Table 14. Phase 2: ANOVA Intrinsic Clothing Insulation

Source	df	Sum of Squares	Mean Square	F	Sig.
Ballistic Material	1	0.0019360	0.0019360	51.08	**<.0001**
Armor System (QG)	4	0.0485458	0.0121365	320.22	**<.0001**
QG * Ballistic Material	4	0.0001011	0.0000253	0.67	0.6223
Error	20	0.0007580	0.0003790		
Corrected Total	29	0.0513410			

Results of analysis of variance for intrinsic clothing insulation indicated a significant armor system effect, $F(4,20) = 320.22$, p <.0001), as shown in Table 14. Figure 19 presents the Post Hoc Tukey comparison analysis with the QuadGard™ systems listed from highest to lowest for intrinsic clothing insulation. There were four groups formed. All configurations of the QG V armor system differed significantly from each other, except for QG V Arms and QG V Upper Legs that did not differ significantly from each other. It is interesting to note that the more surface area covered by the larger QG V modules, resulted in smaller heat loss from conduction, which resulted in higher intrinsic clothing insulation.

Table 15. Phase 2: Intrinsic Clothing Insulation Means

R_{cl}		QG V		QG V Arms		QG V Legs		QG V Upper Arms		QG V Upper Legs	
(°C m^2/W)		K	D	K	D	K	D	K	D	K	D
	Mean	0.134	0.115	0.047	0.035	0.091	0.080	0.023	0.005	0.041	0.022
	SD	0.010	0.004	0.002	0.008	0.004	0.004	0.002	0.005	0.012	0.003

Figure 19. Significant Differences for Intrinsic Clothing Insulation among Phase 2 Armor Systems Based on the Post Hoc $Tukey_{0.05}$ Analysis

QG V	QG V Legs	QG V Arms	QG V Upper Legs	QG V Upper Arms
0.1245a				
	0.08567b			
		0.04100c	0.03150c	
				0.01417d

Intrinsic Clothing Evaporative Resistance

A factorial ANOVA was performed to find out if there were significant differences by treatment for intrinsic clothing evaporative resistance. There was no significant two-way armor system-by-ballistic material interaction for intrinsic clothing evaporative resistance, $F(4,20) = 1.99$, $p = .1348$, as shown in Table 16. A significant ballistic material effect $F(1,20) = 31.72$, $p < .0001$) was found. Table 17 shows Kevlar® consistently measured higher in intrinsic clothing evaporative resistance (R_{ecl}) than Dyneema® regardless of design. These results are similar and consistent with Phase 1.

Table 16. Phase 2: ANOVA Intrinsic Clothing Evaporative Resistance

Source	df	Sum of Squares	Mean Square	F	Sig.
Ballistic Material	1	79.1537630	79.1537630	31.72	**<.0001**
Armor System (QG)	4	2930.5234060	732.6308510	293.63	**<.0001**
QG * Ballistic Material	4	19.8664300	4.9666080	1.99	0.1348
Error	20	49.9015910	2.4950800		
Corrected Total	29	3079.4451900			

Analysis of variance for intrinsic clothing evaporative resistance indicated a significant armor system effect, $F(4,20) = 293.63$, $p < .0001$). Therefore, the null hypothesis stating that there was no significant difference for intrinsic clothing evaporative resistance between QuadGard™ V, QG V Arms, QG V Legs, QG V Upper Arms, and QG V Upper Legs, was rejected. Table 14 presents the intrinsic clothing evaporative resistance means for all armor systems and ballistic materials tested. Considering that QG V covers most of the arms and legs, it is not surprising that QG V had the highest amount of intrinsic clothing evaporative resistance, followed by QG V Legs, QG V Arms, QG V Upper Legs, and QG V Upper Arms. Again, it is not surprising that the garment segment covering the least area, QG V Upper Arms, measured the least amount of intrinsic clothing evaporative resistance. Regardless of ballistic material, the armor systems tested in Phase 2 provided a trend where the highest amount of intrinsic clothing evaporative resistance was indicative of the amount of coverage provided by the armor system. This is a positive finding, as are the results of intrinsic clothing evaporative resistance showing that the modularity of QG V is beneficial for soldiers' thermal well-being when their activities and the level of threat changes.

Table 17. Phase 2: Intrinsic Clothing Evaporative Resistance

R_{ecl}		QG V		QG V Arms		QG V Legs		QG V Upper Arms		QG V Upper Legs	
(Pa m^2/W)		K	D	K	D	K	D	K	D	K	D
	Mean	34.313	28.262	10.126	8.500	19.142	17.151	4.801	2.278	9.624	5.572
	SD	2.111	2.062	1.846	0.618	1.896	0.257	0.684	2.227	1.797	0.372

Figure 20 presents the Post Hoc Tukey comparison analysis with the QuadGard™ systems listed from left to right with the highest to lowest amount of intrinsic clothing evaporative resistance. Four groups were formed. All configurations of QG V armor systems differed significantly from each other in intrinsic clothing evaporative resistance, except for QG V Arms and QG V Upper Legs that did not differ significantly from each other.

Figure 20. Significant Differences for Intrinsic Clothing Evaporative Resistance among Phase 2 Armor Systems Based on the Post Hoc $Tukey_{0.05}$ Analysis

QG V	QG V Legs	QG V Arms	QG V Upper Legs	QG V Upper Arms
31.2873a	18.1462b	9.3128c	7.5980c	3.5393d

Micro-climate Temperature

Temperature sensors, which were placed above the thigh pockets of the BDU pants and under the armor system were used to measure the micro-climate temperature between the BDU and the QuadGard™ V systems. A factorial ANOVA was performed to find out if there were significant differences by treatment for micro-climate temperature. There was no significant two-way armor system-by-ballistic material interaction for micro-climate temperature, $F(4,20) = 2.60$, $p = .0668$, as shown in Table 18.

Table 18. Phase 2: ANOVA Micro-climate Temperature

Source	df	Sum of Squares	Mean Square	F	Sig.
Ballistic Material	1	0.3411200	0.3411200	0.84	0.3709
Armor System (QG)	4	136.7501375	34.1875344	83.98	**<.0001**
QG * Ballistic Material	4	4.2410791	1.0602698	2.6	0.0668
Error	20	8.1421100	0.4071055		
Corrected Total	29	149.4744467			

Table 18 presents the results of analysis of variance which indicated that there was no significant ballistic material effect for micro-climate temperature, $F(1,20) = .84$, $p = .3709$. Therefore, the null hypothesis stating that there was no significant difference for micro-climate temperature between Kevlar® and Dyneema® was not rejected.

Analysis of variance for micro-climate temperature indicated a significant armor system effect, $F(4,20) = 83.98$, $p < .0001$, as shown in Table 18. Therefore, the null hypothesis stating that there was no significant difference for micro-climate temperature by armor system was rejected.

Table 19 presents the micro-climate temperature means of the QuadGard™ V system and all of its components by ballistic material.

Table 19. Phase 2: Micro-climate Temperature Means

	QG V		QG V Arms		QG V Legs		QG V Upper Arms		QG V Upper Legs	
°C	K	D	K	D	K	D	K	D	K	D
Mean	34.944	33.853	30.412	31.417	35.061	34.707	30.163	29.334	34.453	34.656
SD	0.218	0.243	0.509	0.972	0.247	0.214	1.224	0.912	0.265	0.503

Figure 21 presents the Post Hoc Tukey comparison analysis with the QuadGard™ V systems listed from highest to lowest in mean micro-climate temperature. Three groups were formed. According to Tukey, QG V Legs, QG V Upper Legs, and QG V had the highest mean micro-climate temperature and were not significantly different from each other. QG V Arms had the second lowest mean micro-climate temperature (°C) and was significantly different from all other QG V components. Finally, QG V Upper Arms had the lowest mean micro-climate temperature (°C) and differed significantly from all other QG V versions. As expected, the two armor systems that did not cover the upper thigh area (QG V Arms and QG V Upper Arms), where the micro-climate temperature sensors were located, had the lowest mean micro-climate temperatures.

Figure 21. Significant Differences for Micro-climate Temperature among Phase 2 Armor Systems Based on the Post Hoc $Tukey_{0.05}$ Analysis

QG V Legs	QG V Upper Legs	QG V	QG V Arms	QG V Upper Arms
34.8840a	34.5545a	34.3987a		
			30.9145b	
				29.7488c

A summary of the statistical analyses of Phase 2 can be seen in Table 20.

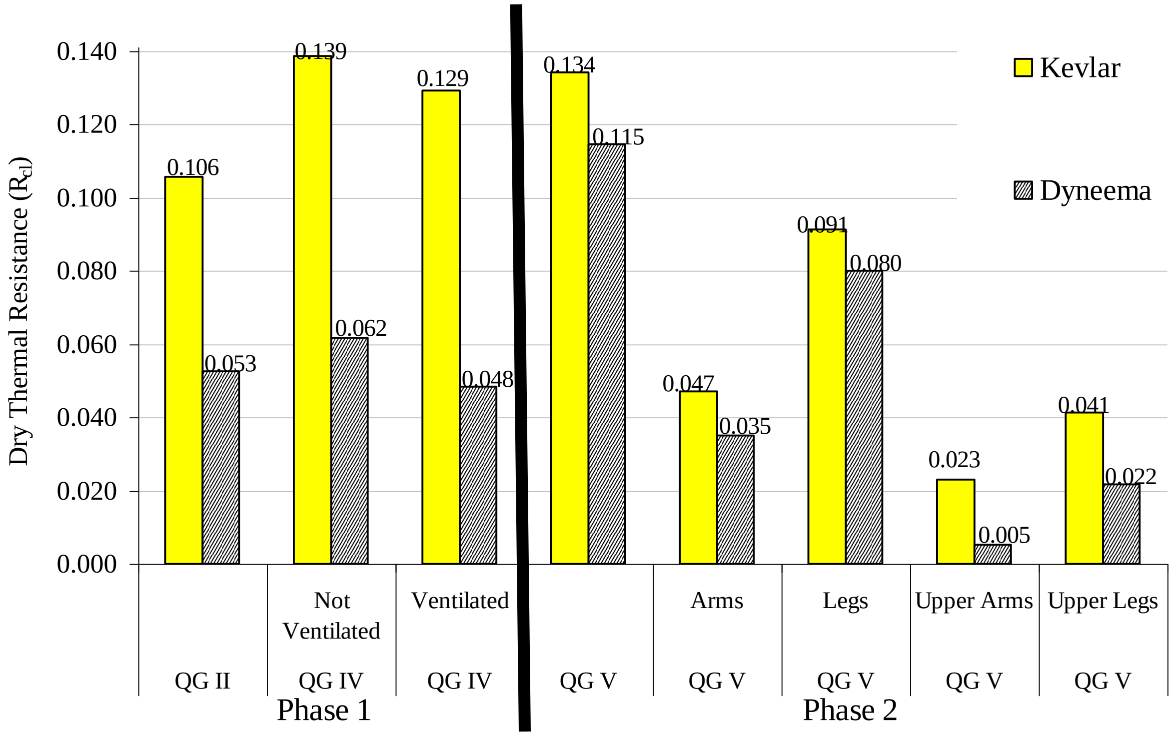
Table 20. Phase 2: Summary of Statistical Results

	Ballistic Material			Armor System	
	Significant Difference	Explanation	Significant Interaction	Significant Difference	Explanation
R_{cl}	Yes	Dyneema® < Kevlar®	No	Yes	4 groups: with 1st group being: QG V Complete, 2nd: Legs, 3rd: Arms & Upper Legs, 4th: Upper Arms
R_{ecl}	Yes	Dyneema® < Kevlar®	No	Yes	4 groups: with 1st group being: QG V Complete, 2nd: Legs, 3rd: Arms & Upper Legs, 4th: Upper Arms
Micro-climate Temperature	No		No	Yes	3 groups: 1st group being: QG V Legs, Upper Legs, & Complete, 2nd: Arms, 3rd: Upper Arms
Moisture Retention	Log transformed data; No		No	Log transformed data; Yes	4 groups: 1st group being: QG V Complete & Legs, 2nd: Upper Legs, 3rd: Arms, 4th: Upper Arms

Summary and Discussion of Both Phases

Heat transmitted from the skin to the environment through clothing consists of two parts: dry heat transfer (conduction, convection, and radiation) and evaporative heat transfer (Chen, Fan, & Zhang, 2003; Celcar, Meinander, & Gersak, 2008). Intrinsic clothing insulation is the measurement of resistance to dry heat transfer, and intrinsic clothing evaporative resistance is the measurement of resistance to evaporative heat transfer. Lower intrinsic clothing insulation and intrinsic clothing evaporative resistance would make the wearer more comfortable in warm climates, especially when worn by a person performing a high rate of physical activity in a warm climate, such as a soldier or firefighter. Regardless of the armor system, the results clearly indicate that with similar protection level, the ballistic material, Dyneema®, consistently measured lower in intrinsic clothing insulation and intrinsic clothing evaporative resistance than the ballistic material, Kevlar®, as shown in Figures 22 and 23.

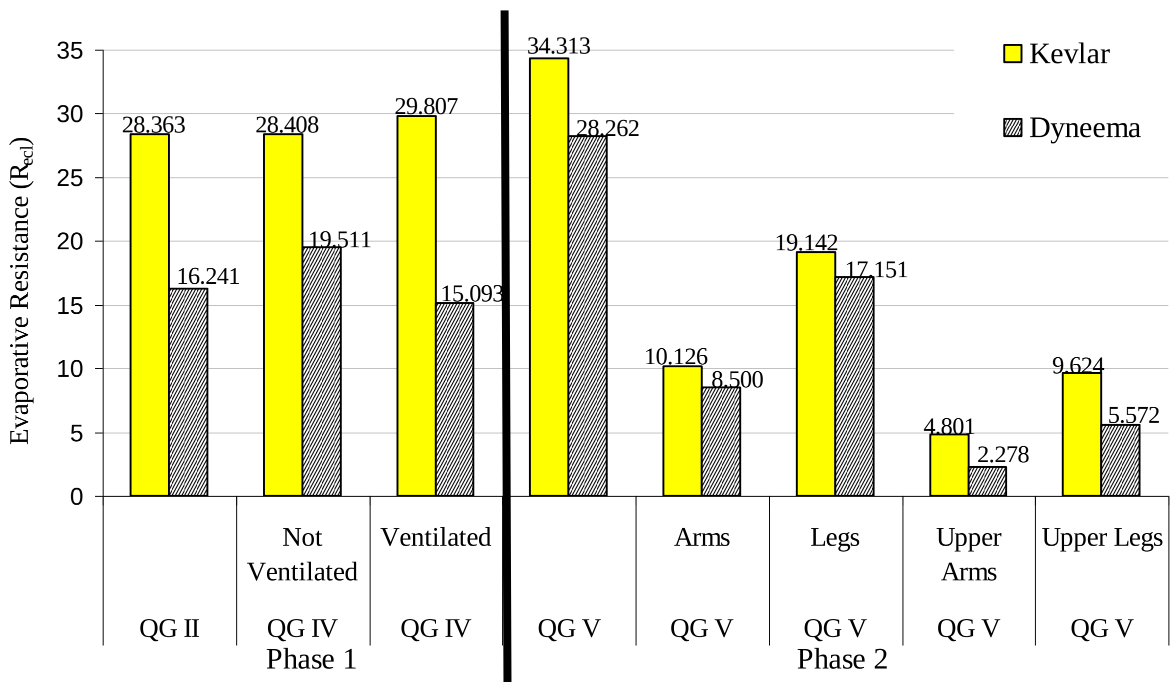
Figure 22. Summary: Intrinsic Clothing Insulation Means for Dyneema® and Kevlar® by Armor System



When considering the armor systems, QG V Complete had the highest amount of intrinsic clothing insulation, with QG IV Not Ventilated have the next highest amount of intrinsic clothing insulation. The armor system with the third highest amount of intrinsic clothing insulation was QG II, which is followed closely by QG IV Ventilated and QG V Legs. QG V Arms had the sixth highest amount of intrinsic clothing insulation and was similar to QG V Upper Legs. As expected, QG V Upper Arms, which is the body armor that covers the least amount of body surface had the lowest amount of intrinsic clothing insulation. The fact that QG II, QG IV Ventilated, and QG V Legs followed QG IV Not Ventilated closely and were similar is a positive finding, which indicates that the ventilation feature of the design does have the potential to reduce the intrinsic clothing insulation of the body armor.

Similarly, when considering intrinsic clothing evaporative resistance, QG V consistently measured the highest in intrinsic clothing evaporative resistance regardless of the ballistic material. This was expected, since QG V covered more surface area than the other armor systems. QG IV Ventilated measured the next highest, QG IV Not Ventilated and QG II following closely with third and fourth highest in intrinsic clothing evaporative resistance, all in Kevlar. In contrast, when considering the ballistic material, Dyneema®, QG IV Not Ventilated measured the next highest, followed closely by QG II, and QG IV Ventilated.

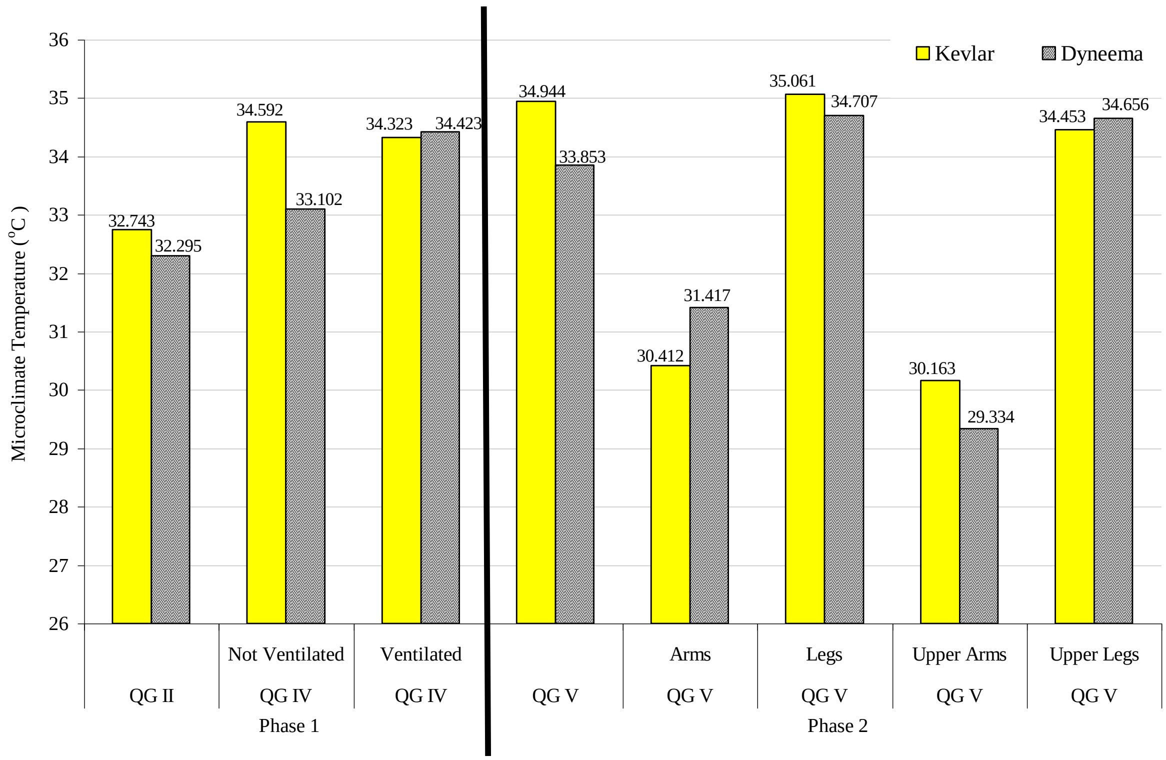
Figure 23. Summary: Intrinsic Clothing Evaporative Resistance Means for Dyneema® and Kevlar® by Armor System



When considering the armor systems, QG V Complete had the highest amount of intrinsic clothing evaporative resistance, with QG IV Not Ventilated have the next highest amount of intrinsic clothing evaporative resistance. QG IV Ventilated and QG II had virtually the same amount of intrinsic clothing evaporative resistance and followed close behind QG IV Not Ventilated. QG V Legs had the fifth highest amount of intrinsic clothing evaporative resistance. QG V Arms had the sixth highest amount of intrinsic clothing evaporative resistance followed closely by QG V Upper Legs. As seen earlier, QG V Upper Arms had the lowest amount of intrinsic clothing evaporative resistance. Once again, the findings were positive, because the ventilation feature in QG IV resulted in QG IV Ventilated and QG II having similar levels of intrinsic clothing evaporative resistance.

It is desirable for micro-climate temperature to be as low as possible for clothing worn by a person with a high rate of physical activity in a warm climate, such as a soldier or firefighter. Mean micro-climate temperature for all armor systems ranged from 29°C in Dyneema® to 35°C in Kevlar®, as shown in Figure 24. Lower mean micro-climate temperatures were found for QG V Upper Arms and QG V Arms regardless of ballistic material. This was expected as the micro-climate temperature sensors were placed above the BDU pant pocket and as such, the sensors were not under an armor system when the modular segments tested covered only the arm area of the manikin. The findings are positive when considering that the mean micro-climate temperatures for the armor systems with most of the arm and leg coverage were similar. These findings appear to indicate that a soldier could wear an armor system with the greatest amount of surface coverage without a large increase in micro-climate temperature. However, it is important to remember that the core temperature of the thermal manikin was maintained at a constant temperature, whereas the core temperature of a human being may be raised if the person has a high rate of physical activity in a warm climate. This may result in a different micro-climate temperature results on a human subject wearing an armor system with the greatest amount of surface coverage.

Figure 24. Summary: Micro-climate Temperature Means for Dyneema® and Kevlar® by Armor System

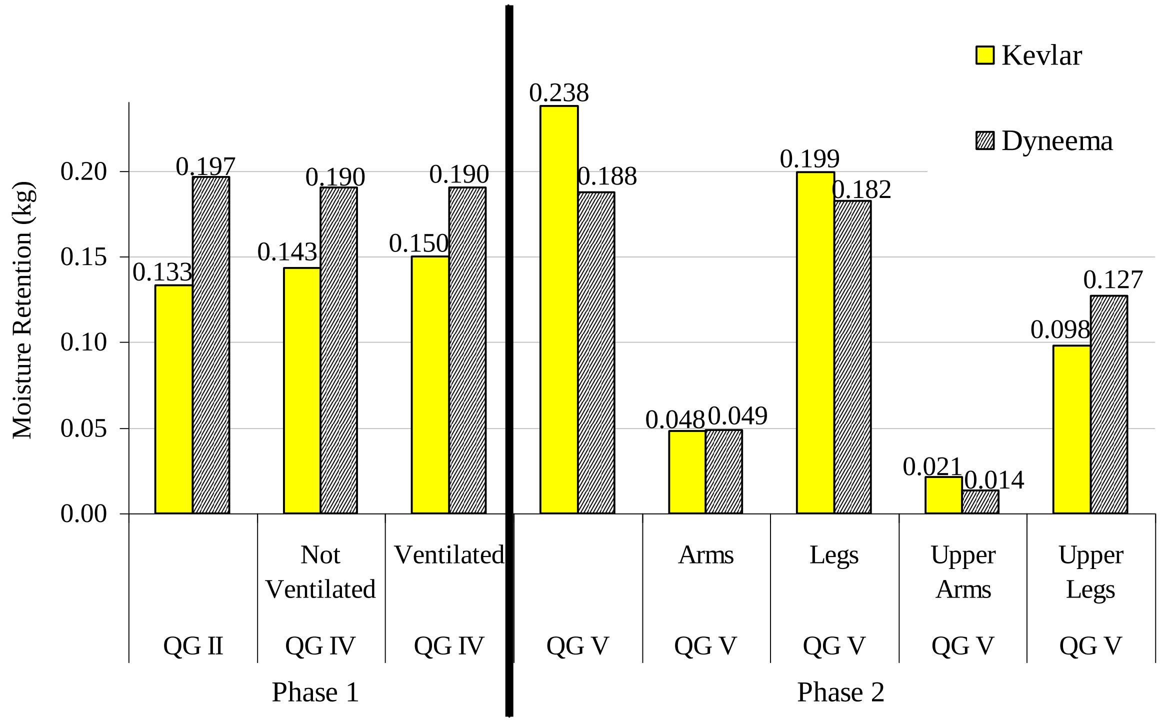


It is well documented that several factors affect the body's ability to cool itself during extremely hot weather or during high levels of physical activity or physical/emotional stress (Craven & Settles, 2006; Lawson, Crown, Ackerman, & Dale, 2004; Bouskill, Havenith, Kuklane, Parsons, & Withey, (2002). The literature clearly indicates that when the humidity is high, sweat will not evaporate as quickly, which prevents the body from releasing heat quickly (Heckert, 2008; Song, 2003). Garments that are fully saturated, because the saturation impedes the garment's ability to dissipate the vapor to the environment and in extension to transfer heat, can exacerbate this phenomenon (Heckert, 2008). Alternatively, it is also true that garments that are impermeable have higher levels of dry thermal or evaporative resistance, reducing the human body's ability to cool itself (Zhou, Li, Chung, Tokura, Gohel, Kwok, & Feng, 2007; Fan, et al., 2005; Bouskill, et al., 2002; Holmer, 1995). Therefore, low moisture retention would make the wearer with a high rate of physical activity, such as a soldier or firefighter, more comfortable in a warm climate. Figure 25 presents the summary of moisture retention for all armor systems tested in both Phases 1 and 2.

The results from Phase 1 clearly indicate that the ballistic material, Dyneema® retained the highest amounts of moisture. However, this pattern is not as straight forward in Phase 2, where the results indicate that Kevlar® retained the highest level of moisture in QG V, QG V Legs, and QG V Upper Arms. In contrast, Dyneema® retained the highest level of moisture in only one armor system, QG V Upper Legs; whereas, QG V Arms retained the same amount of moisture retention in both ballistic materials.

In this study, QG V provided the most protective coverage and QG II provided the least amount of protective coverage, yet QG V does not consistently retain the highest level of moisture. It is interesting to note that QG II, QG IV Not Ventilated, QG IV Ventilated, QG V, and QG V Legs retained similar amounts of moisture for the ballistic material, Dyneema® ($M = 0.2$). This is a positive finding, because it indicates that the armor system with the highest amount of protection does not necessarily gain a proportionate amount of weight from moisture retention.

Figure 25. Summary: Moisture Retention Means for Dyneema® and Kevlar® by Armor System



Conclusions & Implications

Intrinsic Clothing Insulation and Intrinsic Clothing Evaporative Resistance

Regardless of the armor system, the results clearly indicate that the ballistic material, Dyneema®, consistently measured lower in intrinsic clothing insulation and intrinsic clothing evaporative resistance than Kevlar®, as shown in Figures 21 and 22. This finding indicates that Dyneema® would be a good choice of ballistic material to use in future body armor systems, including the ballistic vest worn by soldiers. When considering the full armor systems, QG II tended to measure lower in both intrinsic clothing insulation and intrinsic clothing evaporative resistance as compared to QG IV Ventilated, QG IV Not Ventilated, and QG V Complete. It should be noted that QG II and QG IV Ventilated measured similarly. Since QG II covers the least amount of surface area and provides the least amount of protection, it would be expected that QG II would measure the lowest in both intrinsic clothing insulation and evaporative resistance. However, intrinsic clothing insulation and evaporative resistance means, as seen in Figures 21 and 22, indicate that design features have the potential to reduce thermal stress on the human body when protective clothing is necessary.

It was expected that QG V Complete, which covers the largest amount of body surface area, would have the largest intrinsic clothing insulation and intrinsic clothing evaporative resistance. It is also expected that as coverage is reduced, thermal resistance of the armor system would also reduce. This does not detract from the fact that the modular design of QG V allows the military personnel to adjust the amount of coverage to meet the need as the situation requires. The ability to adjust with the situation allows the soldier to remain active with less thermal stress and without reducing the level of protection. The results show that the modularity of QG V is beneficial for soldiers' when their activities and the level of threat changes. The findings from this study support the findings of Mullett & Chen that found that the surface area of the garment is related to the dry thermal resistance and that the garment design, as well as the fit of the garment, can affect the total insulation value of the garment (2006).

Micro-climate Temperature

It is important to remember that thermal manikins do not simulate the human body physiologically, they simply simulate the local mean skin temperature of a human being (McCullough, 2005b). As such, the core temperature of the thermal manikin was maintained at a constant temperature, whereas a real person's core temperature would fluctuate with different activities and external climate influence. The micro-climate temperature was measured with a microclimate temperature sensor placed above the BDU pant pocket, which is one layer of fabric removed from the skin of the thermal manikin. There was a significant armor system effect for micro-climate temperature in both Phases. It was expected that QG V Arms and QG V Upper Arms would have the lowest micro-climate temperature because there was no armor system over the micro-climate temperature sensor with these armor systems. It was also expected that the armor system that covers the largest amount of body surface area, QG V Complete, would have the highest micro-climate temperatures. However, QG V Legs and QG V Upper Legs produced micro-climate temperatures that were not significantly different from each other and QG V Complete. Figure 24 presents that micro-climate temperature for QG IV Ventilated and QG IV Not Ventilated were similar to QG V Complete, QG V Legs, and QG V Upper Legs. The design of QG II with the open thigh area helped to keep micro-climate temperature lower. In fact, the micro-climate temperatures for the full armor systems that covered the largest amount of surface area only ranged from approximately 32.3°C to 35°C, less than 3 degrees. These findings suggest that covering the leg resulted in a higher micro-climate temperature. Alternatively, when you consider that QG V provides more coverage and protection, the micro-climate temperature increase is small. These findings suggest that a soldier could wear an armor system with the greatest amount of surface coverage without a large increase to the micro-climate temperature. It would be interesting and could benefit the future development of body armor systems to learn whether the micro-climate temperature would be different when the different armor systems are worn by a real person, not a thermal manikin.

Moisture Retention

Evaporation could be hampered due to moisture forming between the layers of Dyneema® and not escape due to the non-woven structure that does not have open areas to promote the evaporation of moisture. Li, Barker, & Deaton found in their study that with test garments that did not fit the manikin, convection occurred within the air trapped between the skin and the inner thermal liner, which encumbered heat loss (2007). Interestingly, it is possible that the moisture retained in the armor systems could have reduced the intrinsic thermal insulation.

In the case of Phase 1, the ballistic material, Kevlar® consistently retained the lowest amount of moisture. However, this was not the case in Phase 2. There is not a definitive reason for the difference in moisture retention between the two ballistic materials. Prior to the completion of this research, it was thought that Kevlar® would absorb more moisture because there are more layers of Kevlar® than Dyneema® and due to the balanced, plain weave that forms Kevlar®. These findings are interesting and warrant further investigation.

This study was completed on a static thermal manikin that sweats at a constant and consistent rate. A human wearing QuadGard™ would not normally sweat at such a constant and consistent rate. It would be interesting to complete this study on human subjects in a wear study that simulates their normal work activity, which has the potential to lower the intrinsic clothing evaporative resistance measurement. It would benefit the future development of body armor systems to document the perception of subjects while wearing the QuadGard™ systems.

References

ASTM (2005). *Annual Book of the ASTM Standards: Textiles*. Philadelphia: American Society for Testing and Materials.

Beckman, R. J. & Tietjen, G. L. (1973). Upper 10% and 25% points of the maximum F ratio. *Biometrika*, *60*(1), 213-214.

Bouskill, L. M., Havenith, G., Kuklane, K., Parsons, K. C., & Withey, W. R. (2002). Relationship between clothing ventilation and thermal insulation. *Journal of Occupational and Environmental Hygiene*, *63*(3), 262-268.

Box, G. E. P. & Cox, D. R. (1964). An analysis of transformations. *Journal of Royal Statistical Society*, *26*(2), 211-252.

Celcar, D., Meinander, H., & Gersak, J. (2008). Heat and moisture transmission properties of clothing systems evaluated by using a sweating thermal manikin under different environmental conditions. *International Journal of Clothing Science and Technology*, *20*(4), 240-252.

Chen, S. Y, Fan, J. & Zhang, W. (2003). Clothing thermal insulation during sweating. *Textile Research Journal*, *73*(2), 152-157.

Craven, B. A. & Settles, G. S. (2006). A computational and experimental investigation of the human thermal plume. *Journal of Fluids Engineering, 128,* 1251-1258.

Fan, J., Chen, Y. S., & Zhang, W. (2005). Clothing thermal insulation when sweating and when non-sweating. In Y. Tochihara & T. Ohnaka (Eds.), *Environmental Ergonomics: The Ergonomics of Human Comfort, Health and Performance in the Thermal Environment* (pp 315-319). Oxford, UK: International Conference on Engineering Education.

Freund, R. J. & Wilson, W. J. (2003). *Statistical Methods (2nd ed.)*. San Diego, CA: Academic Press.

Heckert, P. A. (June 10, 2008). Why evaporating sweat cools our bodies in hot weather. Retrieved from http://physics.suite101.com/article.cfm/physics_of_sweating

Holmer, I. (1995). Protective clothing and heat stress. *Ergonomics, 38*, 166-182.

Holmer, I, Nilsson, H., Havenith, G. & Parsons, K. (1999). Clothing convective heat exchange-Proposal for improved prediction in standards and models. *Annals of Occupational Hygiene, 43*(5), 329-337.

Kamenidis, P. (2009). *Effect of trapped air on heat and moisture resistance of multi-layered soft body armors.* Unpublished master's thesis, *Dissertation Abstracts* (AAT 1465108). Oklahoma State University, Stillwater.

Lawson, L. K., Crown, E. M., Ackerman, M. Y., & Dale, J. D. (2004). Moisture effects in heat transfer through clothing systems for wildland firefighters. *International Journal of Occupational Safety and Ergonomics, 10*(3). 227-238.

Li, J., Barker, R. L., & Deaton, A. S. (2007). Evaluating the effects of material component and design feature on heat transfer in firefighter turnout clothing by a sweating manikin. *Textile Research Journal, 77*(2), 59-66.

Matic, P., Hubler, G. K., Sprague, J. A., Simmonds, K. E., Rupert, N. L. Bruno, R. S., Frost, J. J., Branson, D. H., Farr, C., & Peksoz, S. (2006). Quadgard™ arm and leg protection against ied's. Technical report, *Naval Research Laboratory Review*, 73-81.

McCullough, E. A. (2005a). Evaluation of protective clothing systems using manikins. In R. A. Scott (Eds.), *Textiles for protection* (pp217-232).Cambridge, England: Woodhead Publishing Limited.

McCullough, E. A. (2005b). The use of thermal manikins to evaluate clothing and environmental factors. In Y. Tochihara & T. Ohnaka (Eds.), *Environmental Ergonomics: The Ergonomics of Human Comfort, Health and Performance in the Thermal Environment Environmental* (pp 403 – 407). Oxford, UK: International Conference on Engineering Education.

Mullet, K. & Chen, H. (2006). Thermal insulation of three garment sleeve structures. In J. Fan (Eds.), *Thermal Manikins and Modelling* (pp 375-380). Hong Kong Polytechnic University Reprographic Unit: Sixth International Thermal Manikin and Modelling Meeting (613M).

Peksoz, S., Branson, D. H., & Farr, C. A. (2007). QuadGard™: *A Design Process*. Paper presented at the 2007 ITAA Annual Conference, Los Angeles, CA. Abstract retrieved from http://www.itaaonline.org

Song, C. Y., (2003). The development of a perspiring fabric manikin for the evaluation of clothing thermal comfort. *Dissertation Abstracts International* (UMI 3080246). Hong Kong Polytechnic University.

Woodcock, A. H. (1962). Moisture transfer in textile systems, part 1. *Textile Research Journal, 32*, 623-633.

Yun, Z., Zi-ying, W., Er-li, J., Xiao-hong, Z. & Jian-Yong, C. (2006). A comparison of apparatus used to measure thermal insulation properties to determine thermal comfort. In J. Fan (Eds.), *Thermal Manikins and Modelling* (pp 375-380). Hong Kong Polytechnic University Reprographic Unit: Sixth International Thermal Manikin and Modelling Meeting (613M).

Zhang, P., Gong, R. H., Yanai, Y., & Tokura, H. (2002). Influence of clothing material properties on rectal temperature in different environments. *International Journal of Clothing Science and Technology*, *14*, 299-306.

Zhou, L. Y., Li, Y., Chung, J., Tokura, H., Gohel, M. D. I., Kwok, Y. L., & Feng, X. W. (2007). Effects of fabric surface energy on human thermophysiological responses during exercise and recovery. *Fibers and Polymers*, *8*(3), 319-325.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

As long as there is war, there will be soldiers living and fighting in extreme climates. The United States military presence in warm climates continues to be a reality for military personnel. Therefore, the need for ballistic body armor remains, as does the need for the body to remain thermally balanced. QuadGard™ was designed to protect the soldier from loss of limbs by covering them with lightweight and flexible limb body armor. With the continued military presence in warm climates, the thermal properties of QuadGard™ continues to be an important issue, which is the reason for this study.

This study investigated the effects of fabrication and design features on heat and moisture transfer performance of two different ballistic materials, Kevlar® and Dyneema®, and three different QuadGard™ systems: QuadGard™ II, QuadGard™ IV, and QuadGard™ V. The investigation was carried out in an environmentally controlled chamber set at a temperature of $20^{\circ}C \pm 3^{\circ}C$ with a relative humidity of 50% ± 3%. A sweating thermal manikin was used to measure the dry thermal heat resistance and evaporative resistance, from which intrinsic clothing insulation and intrinsic clothing evaporative resistance were calculated. Micro-climate temperature was measured by the thermal manikin and moisture retention was measured by weighing each QuadGard™ body system before and after each test on the thermal manikin.

Four null hypotheses were tested, two for Phase 1 and two for Phase 2. The first hypothesis for Phase 1 stated that:

$H1\text{-}1_0$: There is no significant difference in intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature, and moisture retention for QuadGard™ armor systems II, IV Ventilated, and IV Not Ventilated.

This hypothesis was rejected for intrinsic clothing insulation and was not rejected for intrinsic clothing evaporative resistance and moisture retention. There was a significant two-way armor system-by-ballistic material interaction found for micro-climate temperature, and the simple effect was significant.

$H1\text{-}2_0$: There is no significant difference in intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature and moisture retention for ballistic materials, Kevlar® and Dyneema®.

This hypothesis was rejected for three dependent variables, intrinsic clothing insulation, intrinsic clothing evaporative resistance, and moisture retention. There was a significant two-way armor system-by-ballistic material interaction found for micro-climate temperature, and the simple effect was significant.

Phase 2

$H2\text{-}1_0$: There is no significant difference in intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature and moisture retention for QuadGard™ armor systems V, V *Arms*, V *Legs*, V *Upper Arms*, and V *Upper Legs*.

This hypothesis was rejected for all four dependent variables, intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature, and moisture retention.

$H2\text{-}2_0$: There is no significant difference in intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature and moisture retention for ballistic materials, Kevlar® and Dyneema®.

This hypothesis was rejected for intrinsic clothing insulation and intrinsic clothing evaporative resistance. However, this hypothesis was not rejected for micro-climate temperature and moisture retention.

There was no interaction between the armor systems and ballistic materials tested for intrinsic clothing insulation, intrinsic clothing evaporative resistance, or moisture retention regardless of the testing Phase. There was a significant two-way armor system-by-ballistic material interaction found for micro-climate temperature, and the simple effect was significant. This interaction was most likely due to the weight and drape of the armor system, which was different due to the ballistic material inserts.

The results of this study indicate that when considering full armor systems, QG II, QG IV Ventilated, QG IV Not Ventilated, and QG V Complete, there was a general trend that QG II measured the lowest and QG V measured the highest for all dependent variables: intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature, and moisture retention. This is logical as QG II covers the least amount of body surface and provides the least protection, while QG V covers the most amount of body surface and provides the most protection. Although, QG II means generally were the lowest for all dependent variables, the difference between the lowest mean and the next mean was not always statistically significant for all dependent variables. When considering intrinsic clothing insulation and intrinsic clothing evaporative resistance, QG II and QG IV Ventilated had similar measurements. This is a positive finding, in that a QuadGard™ system with design features that incorporated ventilation may provide more protective coverage without increasing the soldiers thermal burdens. Comparing data for QG V Complete and QG V different configurations in Phase 2, suggests the benefits and support the use of modular armor systems, especially when soldiers have specific assignments that keep them within structures that provide a measure of ballistic protection.

In both Phases, the ballistic material, Dyneema®, measured lower than Kevlar® for intrinsic clothing insulation and intrinsic clothing evaporative resistance regardless of armor system. This trend did not hold true when testing for micro-climate temperature and moisture retention in Phase 1, where Kevlar® measured the lowest. These results were not consistent across all garment treatments tested in Phase 2. QG V, QG V Legs, and QG V Upper Arms measured lower in micro-climate temperature and moisture retention with Dyneema®. However, the opposite occurred when looking at QG V Arms and QG V Upper Legs, where Dyneema® measured higher than Kevlar®. Considering Dyneema® had fewer layers, was less bulky and lighter, it may be a better ballistic material choice than Kevlar®.

As moisture retention failed the Hartley's F_{max} test indicating heterogeneity of variance, the analysis using the logarithmic transformation indicated a significant ballistic material effect. In Phase 2, the analysis using the log transformation indicated a significant difference between the armor systems. The method for determining moisture retention in this study was taken from Celcar, et al., (2008). However, this study did not take into account that more Kevlar® layers were present in the armor systems. As compared to Dyneema® in order to achieve a similar system protection level, which probably influenced the results. Ultimately, retention of moisture adds weight to the armor systems.

In conclusion, this study built upon and added to the knowledge base for designing body armor systems and the use of sweating, thermal manikins to evaluate the intrinsic clothing insulation and the intrinsic clothing evaporative resistance of protective garments. This study, along with earlier studies, supports the idea that fabrication, and garment ensemble design does affect the intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature, and moisture regain (Holcombe, 1986; Li, et al., 2007; Mullet & Chen, 2006; Bouskill, et al., 2002).

Limitations

This study was limited to the comparison and evaluation of two ballistic materials: Kevlar® and Dyneema® on heat and moisture transfer performance of three different QuadGard™ systems: QuadGard™ II, QuadGard™ IV, and QuadGard™ V. This study was limited to tests performed using a sweating, thermal manikin designed to simulate human thermal and moisture response in interaction with the environment, but it does not have a human being's metabolism and physiological responses to environment change, physical activity, and weight of clothing. So, a human subject test is necessary to confirm findings from this study to humans. This study was limited to one set of environmental temperature and relative humidity conditions, minimal air movement, and a thermal manikin held in a static state.

Recommendations for Further Research

The following are recommended for further research:

1. Conduct a similar investigation with varying air (wind) speeds.
2. Conduct a similar investigation with varying environmental conditions.
3. Conduct a similar investigation placing micro-climate temperature sensors in different locations.
4. Conduct a similar investigation using an alternate method for measuring moisture retention.
5. Conduct an investigation using human subjects walking on a treadmill to simulate the level of physical activity expected from a soldier today.
6. Conduct an investigation using human subjects in a small-scale field test.

REFERENCES

ASTM (2007). *Annual Book of the ASTM Standards: Textiles*. Philadelphia: American Society for Testing and Materials.

ASTM (2005). *Annual Book of the ASTM Standards: Textiles*. Philadelphia: American Society for Testing and Materials.

ASTM (1990). *Annual Book of the ASTM Standards: Textiles*. Philadelphia: American Society for Testing and Materials.

Adams, P. S., Slocum, A., & Keyserling, W. (1994). A model for protective clothing effects on performance. *International Journal of clothing Science and Technology*, *6*(4), 6-16.

Aisen, M. (July, 2004). Amputation Research is Focus of VA 'QUERI' Meeting. U. S. Medicine. Retrieved June 9, 2008 from Research database. (http://www.usmedicine.com/column.cfm?columnID=177&issueID=64).

Anderson, C. J. (1999). *Relationships between physical textile properties and human comfort during wear trials of chemical biological protective garment systems.* Unpublished master's thesis, University of Alberta, Edmonton, Canada.

Barker, D. W., Kini, S., & Bernard, T. W. (1999). Thermal characteristics of clothing ensembles for in heat stress analysis. *American Industrial Hygiene 60*(1), 32-38.

Beckman, R. J. & Tietjen, G. L. (1973). Upper 10% and 25% points of the maximum F ratio. *Biometrika*, *60*(1), 213-214.

Bouskill, L. M., Havenith, G., Kuklane, K., Parsons, K. C., & Withey, W. R. (2002). Relationship between clothing ventilation and thermal insulation. *Journal of Occupational and Environmental Hygiene, 63*(3), 262-268.

Box, G. E. P. & Cox, D. R. (1964). An analysis of transformations. *Journal of Royal Statistical Society*, *26*(2), 211-252.

Branson, D. H., Peksoz, S., Ricord, D., Farr, C. A., & Kumphai, P. (2006). Commercializing QuadGard™: body armor: Initial steps. *ITAA Annual Conference*, San Antonio, Texas.

Branson, D. H. & Sweeney, M. (1991). Conceptualization and measurement of clothing comfort: Toward a metatheory. In S. Kaiser & M. L. Damhorst (Eds.), *Critical linkages in textiles and clothing: Theory, method and practice* (pp 94–105). Monument, CO: International Textile and Apparel Association.

Brojeswari, D., Das, A., Kothari, V., Fanguiero, R. & Araújo, M. (2007). Moisture transmission through textiles part 1: Processes involved in moisture transmission and the factors at play. *Autex Research Journal, 7*(2), 100-110.

Carter, R., Cheuvront, S. N., Williams, J. O., Kolka, M. A., Stephenson, L. A., Sawka, M. N. & Amoroso, P. J. (2005). Epidemiology of hospitalizations and deaths from heat illness in soldiers. *Medical Science & Sports Exercise, 37*(8), 1338-1344.

Celcar, D., Meinander, H., & Gersak, J. (2008). Heat and moisture transmission properties of clothing systems evaluated by using a sweating thermal manikin under different environmental conditions. *International Journal of Clothing Science and Technology, 20*(4), 240-252.

Chen, S. Y, Fan, J. & Zhang, W. (2003). Clothing thermal insulation during sweating. *Textile Research Journal, 73*(2), 152-157.

Cheuvront, A. N. & Haymes, E. M. (2001). Ad libitum fluid intake and thermoregulatory responses of female distance runners in three environments. *Journal of Sports Sciences*, *19*, 845-854.

Clark, R. P. & Edholm, O. G. (1985). *Man and His Thermal Environment.* London, England: Edward Arnold Publishers.

Coleman, J. T. (July, 2006). Heat injuries easily prevented. *The NCO Journal, 15*(3), 6.

Collier, B. J. & Epps, H. H. (1999). *Textile Testing and Analysis*. Upper Saddle River, NJ: Prentice-Hall, Inc.

Connolly, C. (December 9, 2004). U. S. combat fatality rate lowest ever; Technology and surgical care at the front lines credited with saving lives. Washington Post, A24.

Conway, G. L. (1997). *Garment and Textile Dictionary.* Albany, NY: Delmar Publishers.

Craven, B. A. & Settles, G. S. (2006). A computational and experimental investigation of the human thermal plume. *Journal of Fluids Engineering, 128*, 1251-1258.

DSM Dyneema (2008). DSM dyneema – lightweight ballistic fibre for vehicle and personal body armour. *DSM Dyneema*. Retrieved September 21, 2009 from http://www.army-technology.com/contractors/personal/dsm-dyneema

Das, B., Das, A., Kothari, V. K., Fanguiero, R., & de Araujo, M. (2007). Moisture transmission through textiles part1: Processes involved in moisture transmission and the factors at play. *AUTEX Research Journal, 7*(2), 100-110.

Dillow, G. (August 4, 2006). Medics carry a double burden. *Orange County Register Communications*. Retrieved January 30, 2009 from http://www.ocregister.com/articles/strong-marines-carries-1233648-st-nvgs

Emery, S. (June 29, 2005). Airman tests new body armor. *Sci-tech News: Blackanthem Military News*. Retrieved January 30, 2009, from http://www.blankanthem.com/scitech/2005062901.html

Endrusick, T., Berglund, L., Gonzalez, J., Gallimore, R., & Zheng, J. (2006). Use of a spacer vest to increase evaporative cooling under military body armour. In J. Fan (Eds.), *Thermal Manikins and Modelling* (pp 375-380). Hong Kong Polytechnic University Reprographic Unit: Sixth International Thermal Manikin and Modelling Meeting (613M).

Epps, H. H. & Song, M. K. (1992). Thermal transmittance and air permeability of plain weave fabrics. *Clothing and Textile Research Journal, 11*(1), 10-17.

Fan, J. (2006a). Recent developments and applications of sweating fabric and applications of sweating fabric manikin-Walter. In J. Fan (Eds.), *Thermal Manikins and Modelling* (pp 375-380). Hong Kong Polytechnic University Reprographic Unit: Sixth International Thermal Manikin and Modelling Meeting (613M).

Fan, J. (2006b). Thermal insulation of three garment sleeve structures. In J. Fan (Eds.), *Thermal Manikins and Modelling* (pp 375-380). Hong Kong Polytechnic University Reprographic Unit: Sixth International Thermal Manikin and Modelling Meeting (613M).

Fan, J. (2006c). Walter's Manual. PolyU Technology and Consultancy Co. Ltd. (PTeC), Institute of Textiles & Clothing, The Hong Kong Polytechnic University

Fan, J., Chen, Y. S., Zhang, W. (2005). Clothing thermal insulation when sweating and when non-sweating. In Y. Tochihara & T. Ohnaka (Eds.), *Environmental Ergonomics: The Ergonomics of Human Comfort, Health and Performance in the Thermal Environment* (pp 315-319). Oxford, UK: International Conference on Engineering Education.

Fan, J. & Qian, X. (2004). New functions and applications of Walter, the sweating fabric manikin. *European Journal of Applied Physiology 92,* 641-644.

Fanger, P. O. (1981). Prediction of local discomfort for man. In K. Cena & J. A. Clark (Eds.). *Studies in Environmental Science: Vol. 10, Bioengineering, thermal physiology and comfort* (pp 221-227). Amsterdam: Elsevier.

Fanger, P. O. (1970). *Thermal comfort: Analysis and applications in environmental engineering.* New York, NY: McGraw-Hill Publishers.

Fourt, L. & Hollies, N. R. S. (1970). *Clothing: Comfort and function.* New York, NY: Marcel Dekker, Inc.

Freund, R. J. & Wilson, W. J. (2003). *Statistical Methods (2nd ed.).* San Diego, CA: Academic Press.

Gadow, R. & von Niessen, K. (2006). Lightweight ballistic with additional stab protection made of thermally sprayed ceramic and cermet coatings on aramide fabrics. *International Journal of Applied Ceramic Technology, 3*(4), 284-292.

Gibson, P., Rivin, D., & Kendrick, C. (2000). Convection/diffusion test method for porous textiles. *International Journal of Clothing Science and Technology, 12* (2), 96.

Gibson, P. W. (1993). Factors influencing steady-state heat and water vapour transfer measurements for clothing materials. *Textile Research Journal*, *63*(12), 749-764.

Gohlke, D. J. (1980). *Improved Analysis of Comfort Performance in Coated Fabrics*. W. L. Gore & Associates, Inc., Newark, DE

Goldman, R. F. (2006). Thermal insulation of three garment sleeve structures. In J. Fan (Eds.), *Thermal Manikins and Modelling* (pp 375-380). Hong Kong Polytechnic University Reprographic Unit: Sixth International Thermal Manikin and Modelling Meeting (613M).

Goldman, R. F. (2005). The four 'Fs" of clothing comfort. In Y. Tochihara & T. Ohnaka (Eds.), *Environmental Ergonomics: The Ergonomics of Human Comfort, Health and Performance in the Thermal Environment* (pp 315-319). Oxford, UK: International Conference on Engineering Education.

Goldman, R. F. (1969). Physiological costs of body armor. *Military Medicine, 134*(3), 204-210.

Gonzalez, J. A., Berglund, L. G., Kolka, M. A., & Endrusick, T. L. (2006). Forced ventilation of protective garments for hot industries. In J. Fan (Eds.), *Thermal Manikins and Modelling* (pp 375-380). Hong Kong Polytechnic University Reprographic Unit: Sixth International Thermal Manikin and Modelling Meeting (613M).

Gonzalez, N. W., Bernard, T. E., Carroll, N. L., Bryner, M. A., & Zeigler, J. P. (2006).

Maximum sustainable work rate for five protective clothing ensembles with respect to moisture vapor transmission rate and air permeability. *Journal of Occupational and Environmental Hygiene, 3,* 80-86.

Grujicic, M., Arakere, G., He, T., Gogulapati, M., & Cheeseman, B. A. (2008). A numerical investigation of the influence of yarn-level finite-element model on energy absorption by a flexible-fabric armour during ballistic impact. *Journal of Materials: Design and Application, 222,* 259-276.

Heckert, P. A. (June 10, 2008). Why evaporating sweat cools our bodies in hot weather. Retrieved from http://physics.suite101.com/article.cfm/physics_of_sweating

Hammer, M. (2003). Window management for energy conservation. University of Department of Family, Youth and Community Sciences, Florida Cooperative Extension Florida IFA Service Extension, Institute of Food and Agricultural Sciences: Publication date: February 2003 FCS3091 EDIS web site at http://edis.ifas.ufl.edu

Hatch, K. L., Woo, S. S., Barker, R. L., Radhakrishnaiah, P., Markee, N. L., & Maibach, H. I. (1990). In vivo cutaneous and perceived comfort response to fabric. *Textile Research Journal, 60*(7), 405-412.

Havenith, G. (2002). Interaction of clothing and thermoregulation. *Exogenous Dermatology, 1*(5), 221-230.

Havenith, G. (1999). Heat balance when wearing protective clothing. *Annals of Occupational Hygiene, 43*(5), 289-296.

Holcombe, B. V. (1986). The role of clothing comfort in wool marketing. *Wool Technology and Sheep Breeding, 34*(2), 80-83.

Holmer, I. (2004). Thermal manikin history and applications. *European Journal of Applied Physiology 92*, 614-618.

Holmer, I, Nilsson, H., Havenith, G. & Parsons, K. (1999). Clothing convective heat exchange-Proposal for improved prediction in standards and models. *Annals of Occupational Hygiene* 43(5), 329-337.

Holmer, I. & Nilsson, H. (1995). Heated manikins as a tool for evaluating clothing. *Annals of Occupational Hygiene 39*, 809-818.

Holmer, I. (1995). Protective clothing and heat stress. *Ergonomics, 38,* 166-182.

Hostetter, K. (1998). Gore-Tex: The fabric that breathes. *Backpacker, 26*(3) 70.

Hsieh, Y. (1995). Liquid transport in fabric structures. *Textile Research Journal, 65*(5), 299-307.

ISO 11092 (1993). Textiles – Physiological effects – Measurements of thermal and water-vapour resistance under steady state conditions (sweating guarded-hot plate text). *International Organization for Standardization*. Geneva. Switzerland.

Kadolph, S. J. (2007). *Textiles (10th ed.).* New Jersey: Prentice-Hall.

Kamenidis, P. (2009). Effect of trapped air on heat and moisture resistance of multi-layered soft body armors. *Dissertation Abstracts* (AAT 1465108). Oklahoma State University.

Kreighbaum, E. & Barthels, K. M. (1985). The skeletal system and its movements. In *Biomechanics: A qualitative approach for studying human movement (2nd ed.)* (pp 19-64). Minneapolis, MN: Burgess Publishing Company.

Kuklane, K., Holmer, I., & Giesbrecht, G., (1999). Change of footwear insulation at various sweating rates. *Applied Human Science, 18*(5), 161-168.

Lawson, L. K., Crown, E. M., Ackerman, M. Y., & Dale, J. D. (2004). Moisture effects in heat transfer through clothing systems for wildland firefighters. *International Journal of Occupational Safety and Ergonomics, 10*(3). 227-238.

Lee, Y. S., Wetzel, E. D., & Wagner, N. J. (2003). The ballistic impact characteristics of Kevlar woven fabrics impregnated with a colloidal shear thickening fluid. *Journal of Materials Science, 38*, 2825-2833.

Levine, L., Sawka, M. N., & Gonzalez, R. R. (1998). Evaluation of clothing systems to determine heat strain. *American Industrial Hygiene Association Journal, 59*(8), 557-561.

Lewis, W. K. (1922). The evaporation of a liquid into gas. *ASME Transactions, 44*, 325-335.

Li, J., Barker, R. L., & Deaton, A. S. (2007). Evaluating the effects of material component and design feature on heat transfer in firefighter turnout clothing by a sweating manikin. *Textile Research Journal, 77*(2), 59-66.

Matic, P., Hubler, G. K., Sprague, J. A., Simmonds, K. E., Rupert, N. L. Bruno, R. S., Frost, J. J., Branson, D. H., Farr, C., & Peksoz, S. (2006). QuadGard™ arm and leg protection against ied's. Technical report, *Naval Research Laboratory Review*, 73-81.

McCullough, E. A. (2005a). Evaluation of protective clothing systems using manikins. In R. A. Scott (Eds.), *Textiles for protection* (pp217-232).Cambridge, England: Woodhead Publishing Limited.

McCullough, E. A. (2005b). The use of thermal manikins to evaluate clothing and environmental factors. In Y. Tochihara & T. Ohnaka (Eds.), *Environmental Ergonomics: The Ergonomics of Human Comfort, Health and Performance in the Thermal Environment Environmental* (pp 403 – 407). Oxford, UK: International Conference on Engineering Education.

McCullough, E. A. (2001). Clever clothing. *Human Ecology, 29*(3), 9-10.

McCullough, E. A. (1993). Factors affecting the resistance to heat transfer provided by clothing. *Journal of Thermal Biology, 18*, 405-407.

Mullet, K. & Chen, H. (2006). Thermal insulation of three garment sleeve structures. In J. Fan (Eds.), *Thermal Manikins and Modelling* (pp 375-380). Hong Kong Polytechnic University Reprographic Unit: Sixth International Thermal Manikin and Modelling Meeting (613M).

Nilsson, H. O. (2004). Comfort climate evaluation with thermal manikin methods and computer simulation models. Thesis. Department of Civil and Architectural Engineering Royal Institute of Technology, Sweden, Department of Technology and Built Environment University of Gavle, Sweden. Stockholm, Sweden: Arbetslivsinstitutet, National Institute for Working Life.

O'Brien, K. K., McPherson, M. K., Alsip, B. & Sawka, M. N. (2003). Case studies of exertional heat injury/stroke in military populations. In Bouchama, A., Parhar, R. S., el-Yazigi, A., Sheth, K. (Eds.) *Recruit Medicine* (pp 493-516). Washington, DC: Department of Defense, Office of the Surgeon General, US Army, Borden Institute.

Parsons, K. C. (2003). *Human thermal environments: The effects of hot, moderate, and cold environments on human health, comfort, and performance.* New York, NY: Taylor & Francis, Inc.

Peake, J. B. (2005). Beyond the Purple Heart – Continuity of Care for the Wounded in Iraq. *The New England Journal of Medicine, 352*(3), 219-222. Retrieved January 29, 2008, from Research database. (Document ID: 782009081).

Peksoz, S., Branson, D. H., & Farr, C. A. (2007). QuadGard™: *A Design Process*. Paper presented at the 2007 ITAA Annual Conference, Los Angeles, CA. Abstract retrieved from http://www.itaaonline.org

Peksoz, S., Branson, D. H., & Farr, C. A. (2007). QuadGard™: A Design Process. *ITAA Annual Conference*, Los Angeles, California.

Potluri, P. & Needham, P. (2005). Technical textiles for protection. In R. A. Scott (Eds.), *Textiles for protection* (pp217-232).Cambridge, England: Woodhead Publishing Limited.

Qian, X. & Fan, J. (2006). Heat and mass transfer from clothing induced by air ventilation. In J. Fan (Eds.), *Thermal Manikins and Modelling* (pp 375-380). Hong Kong Polytechnic University Reprographic Unit: Sixth International Thermal Manikin and Modelling Meeting (613M).

Qian, X. (2005). Prediction of Clothing Thermal Insulation and Moisture Vapour Resistance. *Dissertation Abstracts International* (UMI 3195408). Hong Kong Polytechnic University

Richards, G. M. & McCullough, E. A. (2005). Revised interlaboratory study of sweating thermal manikins including results from the sweating agile thermal manikin. *Journal of ASTM International, 2*(4), Retrieved October 26, 2007 from http://www.astm.org. (Document ID: 36493154).

Rosenfeld, J. V. (May, 2005). War Surgery in Iraq: Treating Bomb Blast and Penetrating Trauma in the Individual. *Military Surgery ANZ Journal of Surgery*, *75*(s1), A84-A-85. Retrieved November 30, 2007, from http://www.blackwell-synergy.com/doi/abs/10.1111/j.1445-2197.2005.03464.x

Rosenfeld, J. V. & Lennarson, P. L. (May, 2005). Why has the Mortality of U.S. Soldiers from Battle Injuries Improved in the Current Iraq War? *Military Surgery ANZ Journal of Surgery*, *75*(s1), A84-A-85. Retrieved November 30, 2007, from http://www.blackwell-synergy.com/doi/abs/10.1111/j.1445-2197.2005.03464.x

Selle, R. R. (2004). The woman who created kevlar. *The World & I, 19*(3), p 44-47.

Shibasaki, M., Wilson, T. E., & Crandall, C. G. (2006). Neural control and mechanisms of eccrine sweating during heat stress and exercise. *Journal of Applied Physiology. 100*(5), 1692-1701.

Shishoo, R. (2002). Recent developments in materials for use in protective clothing. *International Journal of Clothing Science and Technology, 14*(3/4), p 201-215.

SGMA (1997). Sport apparel dictionary of performance fibers, fabrics and finishes. North Palm Beach, FL: Sporting Goods Manufacturers Association.

Smith, O. (2006). Driver's seat: Getting improved equipment into the hands of soldiers. *Armor, 115*(6), 5.

Song, C. Y., (2003). The development of a perspiring fabric manikin for the evaluation of clothing thermal comfort. *Dissertation Abstracts International* (UMI 3080246). Hong Kong Polytechnic University

Sontag, M. S. (1985-86). Comfort dimensions of actual and ideal insulative clothing for older women. *Clothing and Textiles Research Journal*, *4*(1), 9-17.

Tyson, A. S., (2006, January 12). More body armor is on the way for U. S. troops. *The Washington Post*. Retrieved from http://www.washingtonpost.com

U. S. Army Soldier & Biological Chemical Command. (September 10, 2001). Objective force warrior to enhance lethality, survivability. Retrieved January 30, 2009 from SBCCOM-Natick Press Release. (http://www.ssc.army.mil/about/pao/2001/01-48.htm)

U. S. Department of Justice (2008). *Ballistic resistance of body armor, NIJ standard-0101.06*. Retrieved October 5, 2009, from http://www.ncjrs.gov/pdffiles1/nij/223054.pdf

Watkins, S. (1995). *Clothing: The portable environment (2nd ed.).*Ames, IA: Iowa State University Press.

Woo, S. S., Shalev, I., & Barker, R. L. (1994). Heat and moisture transfer through nonwovens fabrics, part 1: Heat transfer. *Textile Research Journal, 64*, 149-162.

Woodcock, A. H. (1962). Moisture transfer in textile systems, part 1. *Textile Research Journal*, *32*, 623-633.

Yun, Z., Zi-ying, W., Er-li, J., Xiao-hong, Z. & Jian-Yong, C. (2006). A comparison of apparatus used to measure thermal insulation properties to determine thermal comfort. In J. Fan (Eds.), *Thermal Manikins and Modelling* (pp 375-380). Hong Kong Polytechnic University Reprographic Unit: Sixth International Thermal Manikin and Modelling Meeting (613M).

Zhang, P., Gong, R. H., Yanai, Y., & Tokura, H. (2002). Influence of clothing material properties on rectal temperature in different environments. *International Journal of Clothing Science and Technology, 14,* 299-306.

Zhou, L. Y., Li, Y., Chung, J., Tokura, H., Gohel, M. D. I., Kwok, Y. L., & Feng, X. W. (2007). Effects of fabric surface energy on human thermophysiological responses during exercise and recovery. *Fibers and Polymers, 8*(3), 319-325.

Zimmerli, T. (2000). Manikin testing of protective clothing - a survey, *Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh volume, ASTM STP 1386*, C.N. Nelson and N. W. Henry, Eds., American Society for Testing and Materials, West Conshohocken, PA.

APPENDICES

APPENDIX A

Air Velocity Measured in Manikin's Environmental Chamber

	Head	Lower	Right shoulder	Left shoulder
	0.45	0.37	0.39	0.46
	0.42	0.33	0.38	0.43
	0.34	0.34	0.44	0.5
Average	0.40	0.35	0.40	0.46
STD	0.06	0.02	0.03	0.04

APPENDIX B

R_{ct} Results For All Treatments of Phase 1

test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ **II**							
Kevlar®				Dyneema®			
0.396	0.362	0.383		0.404	0.308	0.266	
0.324	0.324	0.312		0.283	0.283	0.278	
0.324	0.321	0.300		0.281	0.290	0.276	
0.310	0.314	0.307		0.286	0.297	0.279	
0.306	0.310	0.300		0.280	0.283	0.284	
0.309	0.317	0.293		0.274	0.272	0.282	
0.309	0.303	0.298		0.278	0.284	0.276	
0.307	0.300	0.293		0.274	0.272	0.271	
QuadGard™ **IV Not Ventilated**							
Kevlar®				Dyneema®			
0.519	0.710	0.997		0.391	0.33	0.321	
0.363	0.357	0.380		0.303	0.295	0.292	
0.361	0.340	0.346		0.285	0.284	0.308	
0.340	0.325	0.352		0.295	0.277	0.281	
0.325	0.317	0.349		0.283	0.282	0.286	
0.338	0.316	0.337		0.285	0.268	0.283	
0.322	0.337	0.334		0.279	0.27	0.278	
0.330	0.318	0.334		0.285	0.274	0.274	
QuadGard™ **IV Ventilated**							
Kevlar®				Dyneema®			
0.554	0.408	0.331		0.283	0.248	0.466	
0.352	0.329	0.344		0.268	0.266	0.298	
0.346	0.321	0.348		0.275	0.277	0.308	
0.332	0.327	0.323		0.277	0.284	0.291	
0.328	0.315	0.332		0.275	0.285	0.279	
0.319	0.321	0.334		0.275	0.273	0.284	
0.328	0.319	0.324		0.278	0.276	0.274	
0.322	0.319	0.317		0.278	0.27	0.274	

APPENDIX C

R_{ct} Results For All Treatments of Phase 2

test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ **V**							
Kevlar®				Dyneema®			
0.47	0.562	0.365		0.539	0.606	0.381	
0.358	0.373	0.340		0.337	0.306	0.301	
0.337	0.354	0.312		0.322	0.307	0.306	
0.322	0.344	0.319		0.316	0.323	0.305	
0.325	0.343	0.328		0.319	0.33	0.301	
0.321	0.341	0.330		0.308	0.302	0.312	
0.327	0.328	0.310		0.323	0.288	0.321	
0.319	0.333	0.316		0.31	0.298	0.296	
test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ V Arms							
Kevlar®				Dyneema®			
0.274	0.284	0.333		0.302	0.257	0.245	
0.264	0.275	0.281		0.283	0.266	0.248	
0.265	0.26	0.276		0.265	0.259	0.260	
0.263	0.266	0.278		0.26	0.267	0.254	
0.264	0.255	0.266		0.263	0.26	0.256	
0.265	0.259	0.268		0.266	0.261	0.254	
0.253	0.254	0.265		0.248	0.258	0.246	
0.254	0.253	0.27		0.256	0.258	0.246	
test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ V Legs							
Kevlar®				Dyneema®			
0.489	0.415	0.300		0.362	0.429	0.343	
0.31	0.303	0.312		0.279	0.304	0.303	
0.31	0.296	0.300		0.295	0.286	0.277	
0.292	0.301	0.290		0.28	0.293	0.298	
0.292	0.293	0.306		0.277	0.277	0.285	
0.295	0.299	0.305		0.278	0.281	0.286	
0.299	0.299	0.292		0.284	0.278	0.274	
0.291	0.294	0.300		0		0.279	

test 1	test 2	test 3	**Mean Rct**	test 1	test 2	test 3	**Mean Rct**
QuadGard™ V Upper Arms							
Kevlar®				Dyneema®			
0.261	0.248	0.247		0.226	0.212	0.221	
0.247	0.242	0.248		0.24	0.232	0.232	
0.25	0.249	0.258		0.237	0.24	0.235	
0.239	0.253	0.254		0.241	0.239	0.246	
0.243	0.248	0.249		0.242	0.235	0.248	
0.244	0.264	0.248		0.245	0.23	0.243	
0.245	0.26	0.256		0.243	0.232	0.249	
0.245	0.26	0.254		0.248	0.233	0.249	

test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ V Upper Legs							
Kevlar®				Dyneema®			
0.275	0.261	0.317		0.262	0.247	0.313	
0.262	0.259	0.287		0.257	0.255	0.263	
0.261	0.274	0.272		0.258	0.246	0.253	
0.258	0.258	0.267		0.262	0.255	0.251	
0.257	0.266	0.27		0.265	0.259	0.256	
0.26	0.269	0.265		0.258	0.253	0.251	
0.262	0.264	0.271		0.254	0.252	0.25	
0.256	0.26	0.264		0.253	0.248	0.249	

APPENDIX D

R_{et} Results For All Treatments of Phase 1

test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ II							
Kevlar®				Dyneema®			
47.425	48.954	56.952		40.764	45.667	45.937	
58.322	59.420	60.006		49.016	48.992	48.385	
59.627	60.192	60.718		49.706	48.651	47.852	
60.655	60.532	61.065		49.607	47.872	47.415	
60.647	61.279	61.368		50.053	49.612	47.547	
61.299	60.694	61.987		50.058	49.827	47.818	
60.999	61.450	61.384		50.358	49.585	48.291	
61.402	61.919	62.194		50.221	50.051	48.236	
test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ IV Not Ventilated							
Kevlar®				Dyneema®			
43.670	39.578	37.932		43.937	42.636	49.336	
55.655	54.862	54.453		50.592	48.377	53.989	
57.688	56.307	55.670		51.628	48.164	52.906	
58.440	57.117	55.778		51.406	48.764	54.24	
59.066	57.729	55.852		52.241	48.502	53.721	
58.784	57.767	57.073		52.493	48.876	54.367	
59.595	56.345	56.765		51.851	48.689	54.606	
59.480	56.533	57.473		52.162	48.824	55.376	
test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ IV Ventilated							
Kevlar®				Dyneema®			
43.663	45.180	67.589		44.716	49.545	36.842	
55.113	55.902	67.788		48.667	49.893	45.845	
55.975	57.024	67.966		48.697	48.008	46.066	
56.610	57.110	68.702		48.256	47.497	46.853	
56.974	58.042	68.169		47.887	47.844	47.069	
58.586	57.998	67.735		47.801	48.3	47.462	
57.711	58.150	68.106		47.698	48.615	47.775	
57.951	57.801	68.417		47.464	48.561	48.497	

APPENDIX E

R_{et} Results For All Treatments of Phase 2

test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ **V**							
Kevlar®				Dyneema®			
46.749	46.266	52.163		42.571	48.123	48.159	
59.528	62.219	64.655		54.047	65.965	59.708	
61.783	63.989	66.511		56.303	68.058	60.571	
62.499	64.518	66.135		57.182	68.464	61.322	
62.757	65.445	66.251		57.294	67.708	61.171	
63.008	65.925	66.375		57.719	66.311	61.071	
63.823	67.218	67.466		57.292	67.557	59.706	
64.186	67.455	66.353		58.349	67.533	61.838	
test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ V Arms							
Kevlar®				Dyneema®			
41.895	38.312	35.933		37.555	40.009	44.549	
44.093	41.067	42.231		39.693	41.523	46.975	
44.53	42.236	42.842		40.814	41.848	46.641	
44.621	41.818	42.88		41.316	41.942	47.344	
44.98	42.77	43.139		41.408	41.97	47.663	
44.258	42.576	43.176		41.529	42.252	47.832	
45.881	42.797	43.627		42.166	42.773	48.472	
45.338	42.961	43.604		42.525	42.957	48.587	
test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ V Legs							
Kevlar®				Dyneema®			
38.576	39.352	46.869	**41.599**	39.321	37.281	42.458	
47.949	47.968	54.648	**50.188**	47.913	44.117	51.459	
48.585	48.734	55.503	**50.941**	47.947	45.724	52.889	
50.109	49.12	55.593	**51.607**	48.525	46.099	52.798	
50.246	49.727	55.638	**51.870**	48.41	46.888	53.22	
50.071	49.639	55.552	**51.754**	48.539	46.816	53.422	
49.957	49.412	56.742	**52.037**	49.016	47.246	53.53	
49.955	49.665	56.289	**51.970**	48.1	47.1	53.308	

test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ V Upper Arms							
Kevlar®				Dyneema®			
34.69	36.289	42.25		38.428	34.951	38.832	
36.468	40.304	43.539		39.651	33.961	38.36	
36.595	40.02	43.09		39.961	34.067	38.088	
37.435	39.768	43.321		40.29	34.373	37.575	
37.336	39.74	43.996		40.086	34.738	36.812	
37.21	39.247	44.621		39.925	34.822	37.548	
37.403	39.158	43.785		40.265	35.15	37.376	
37.31	39.361	43.623		40.245	35.087	37.415	
test 1	test 2	test 3		test 1	test 2	test 3	
QuadGard™ V Upper Legs							
Kevlar®				Dyneema®			
38.376	35.749	36.873		34.208	43.084	35.309	
41.723	41.751	44.637		39.483	45.144	43.246	
42.08	41.242	45.914		39.859	44.91	44.438	
42.84	42.136	46.612		40.122	44.987	44.635	
42.51	41.765	46.462		40.08	44.725	45.016	
42.628	41.774	47.238		40.48	45.276	45.224	
42.652	41.848	47.094		40.533	45.41	45.333	
42.932	42.041	47.42		40.496	45.177	45.208	

APPENDIX F

BDU Jacket, BDU Pants, & Interceptor Vest: R_{ct} and R_{et} Test Results

	4 4		4 12		4 24	
	rt	**ret**	**rt**	**ret**	**rt**	**ret**
1	0.23500	35.94600	0.24000	34.25300	0.27600	34.90700
2	0.23700	36.32900	0.23600	34.25700	0.25900	36.15800
3	0.23500	36.24400	0.24200	34.28200	0.59400	25.06200
Average	**0.23567**	**36.17300**	**0.23933**	**34.26400**	**0.37633**	**32.04233**
STD	*0.00115*	*0.20113*	*0.00306*	*0.01572*	*0.18870*	*6.07742*

	5 4		6 8		6 18	
	rt	**ret**	**rt**	**ret**	**rt**	**ret**
1	0.26100	35.51600	0.29500	34.20200	0.25500	39.91900
2	0.26300	34.85800	0.28200	35.58400	0.24300	40.31100
3	0.26100	35.20500	0.26700	35.85500	0.25400	40.24300
Average	**0.26167**	**35.19300**	**0.28133**	**35.21367**	**0.25067**	**40.15767**
STD	*0.00115*	*0.32916*	*0.01401*	*0.88655*	*0.00666*	*0.20947*

VITA

Cathy L. Starr

Candidate for the Degree of

Doctor of Philosophy

Dissertation: THERMAL MANIKIN EVALUATION OF MATERIAL COMPONENT AND DESIGN FEATURES ON HEAT AND MOISTURE TRANSFER OF QUADGARD™

Major Field: Human Environmental Sciences

Biographical:

Education: Completed the requirements for the Doctor of Philosophy in Human Environmental Sciences at Oklahoma State University, Stillwater, Oklahoma in July, 2010.

Completed the requirements for a Masters of Science in Design, Housing, and Merchandising at Oklahoma State University, Stillwater, Oklahoma in May, 2002

Completed the requirements for a Bachelor of Science in Apparel Design and a Minor in Apparel Merchandising at Oklahoma State University, Stillwater, Oklahoma in May, 1998.

Experience: Assistant Professor, Missouri State University, Department of Fashion and Interior Design, Springfield, Missouri, 2009 – present.

Professional Memberships: International Textile and Apparel Association (ITAA), American Association of Textile Chemists & Colorists (AATCC), Phi Kappa Phi, and American Quilter's Society (AQS)

Awards and Recognition:
Best Solution to a Design Problem Award: International Textile & Apparel Association Annual Conference Design Competition, Cincinnati, OH.
NASA Oklahoma Space Grant Consortium $5,000 Fellowship
AAFA Apparel Student of the Year

Name: Cathy L. Starr Date of Degree: July, 2010

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: THERMAL MANIKIN EVALUATION OF MATERIAL COMPONENT AND DESIGN FEATURES ON HEAT AND MOISTURE TRANSFER OF QUADGARD™

Pages in Study: 135 Candidate for the Degree of Doctor of Philosophy

Major Field: Human Environmental Sciences

Scope and Method of Study: The purpose of this study was to examine the intrinsic clothing insulation, intrinsic clothing evaporative resistance, micro-climate temperature, and moisture retention of three armor systems and two ballistic materials, Dyneema and Kevlar. Testing was completed in an environmental chamber set at a temperature of 20°C $\pm$ 3°C with a relative humidity of 50% $\pm$ 3%.

Findings and Conclusions: Test results from Phase 1 indicated that there was a significant ballistic material effect for intrinsic clothing insulation, $F(1,12) = 191.90$, $p < .0001$) and intrinsic clothing evaporative resistance, $F(1,12) = 104.59$, $p < .0001$). For micro-climate temperature there was a significant two-way armor system-by-ballistic material interaction and the simple effects were significant for ballistic material, $F(1,12) = 9.34$, $p = .01$). Since the moisture retention data did not satisfy the assumption of homogeneity of variance, a logarithmic transformation was performed on the data. Analysis of the log transformed data showed a significant ballistic material effect for moisture retention, $F(1,12) = 19.31$, $p = .0009$). Test results from Phase 1 indicated a significant armor system effect for intrinsic clothing insulation, $F(2,12) = 5.71$, $p = .0181$). For micro-climate temperature there was a significant two-way armor system-by-ballistic material interaction and the simple effects were significant for armor system, $F(2,12) = 30.30$, $p < .0001$). Phase 2 results indicated that there was a significant ballistic material effect for intrinsic clothing insulation, $F(1,20) = 51.08$, $p < .0001$) and intrinsic clothing evaporation, $F(1,20) = 31.72$, $p < .0001$). Test results from Phase 2 indicated that there was a significant armor system effect for three dependent variables: 1) intrinsic clothing insulation, $F(4,20) = 320.22$, $p < .0001$); 2) intrinsic clothing evaporative resistance (R_{ecl}), $F(4,20) = 293.63$, $p < .0001$); and 3) micro-climate temperature, $F(4,20) = 83.98$, $p < .0001$). The moisture retention data did not satisfy the assumption of homogeneity of variance, a logarithmic transformation was performed on the data. Analysis of the log transformed data showed a significant armor system effect for moisture retention, $F(4,20) = 107.37$, $p < .0001$). The findings from this study indicated that fabric and garment design influence the thermal burden of the garment ensemble. The findings give merit to and show the benefit of modularity, especially for military personnel who will be in or driving an armored vehicle.

ADVISER'S APPROVAL: Dr. Donna H. Branson